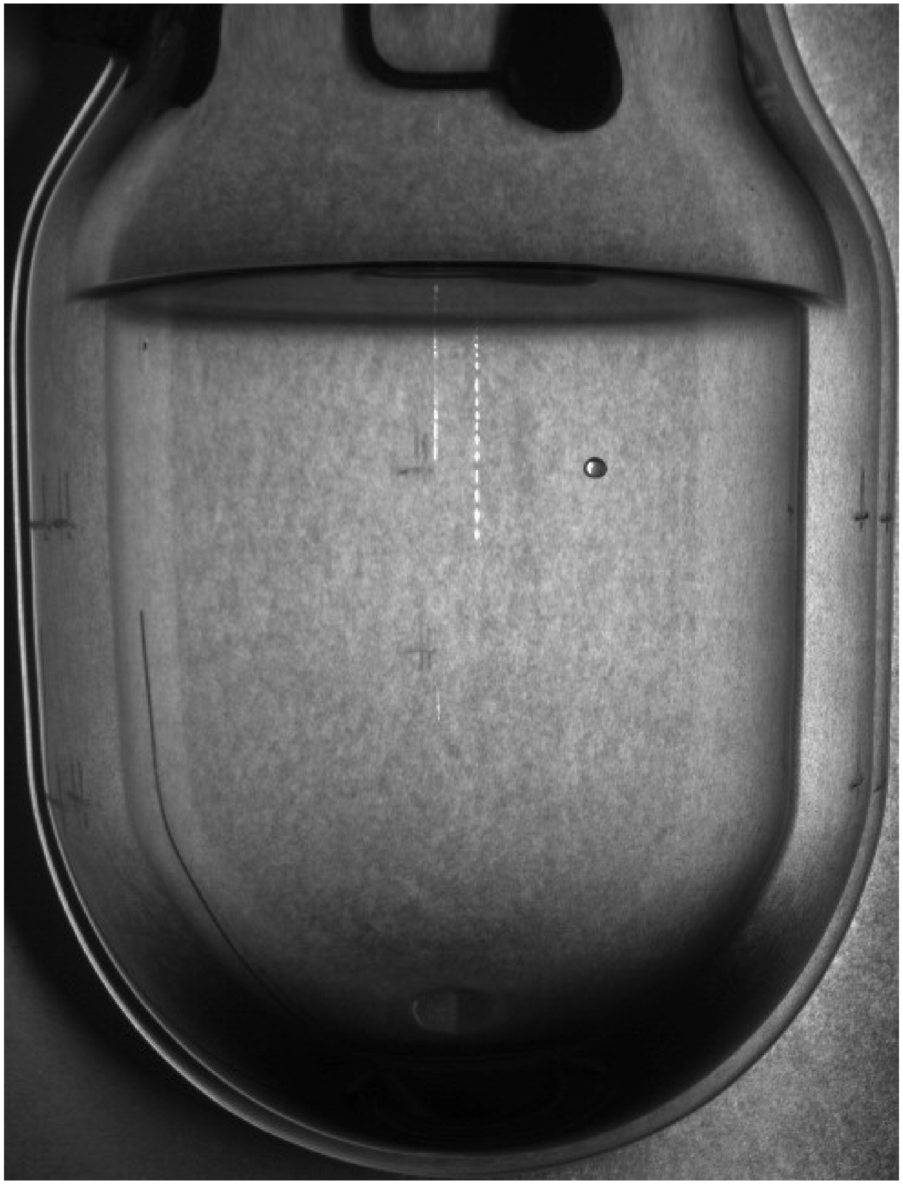
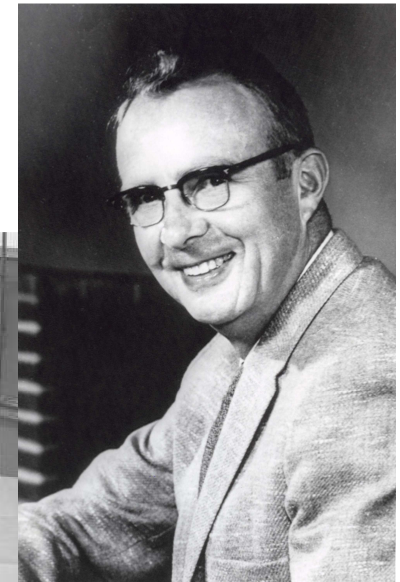
# “PICO– Perspectives Challenges, Plans”

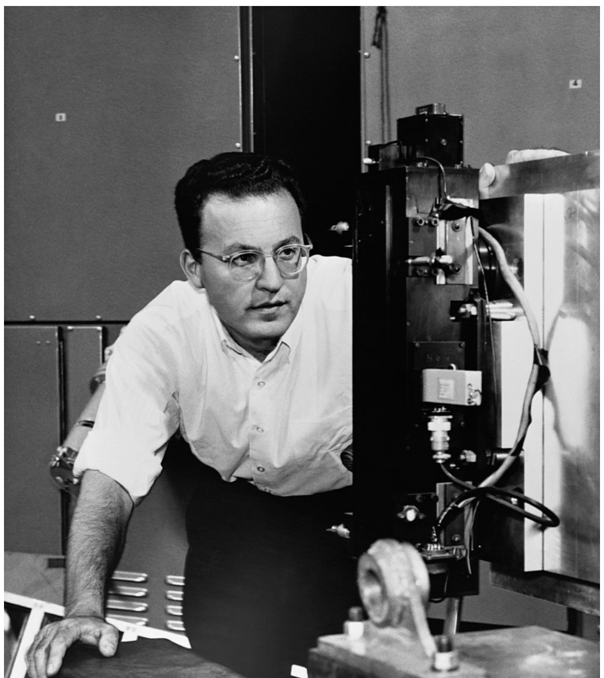


Andrew Sonnenschein, Fermilab

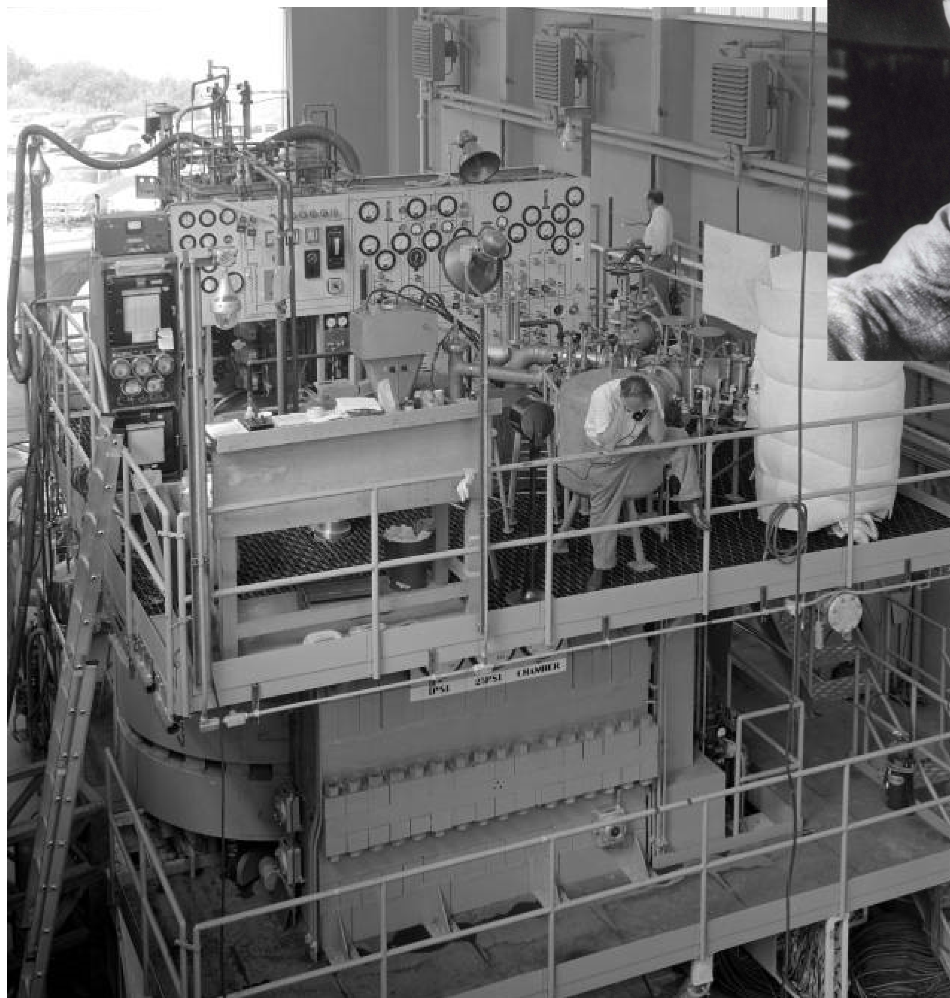
3rd Berkeley Workshop on Direct Detection of Dark Matter, Dec 5, 2016

*In those days, if anybody had an idea, and people thought it was a good idea, then you could start working on it. You didn't write proposals and that sort of stuff.* **Luis Alvarez**





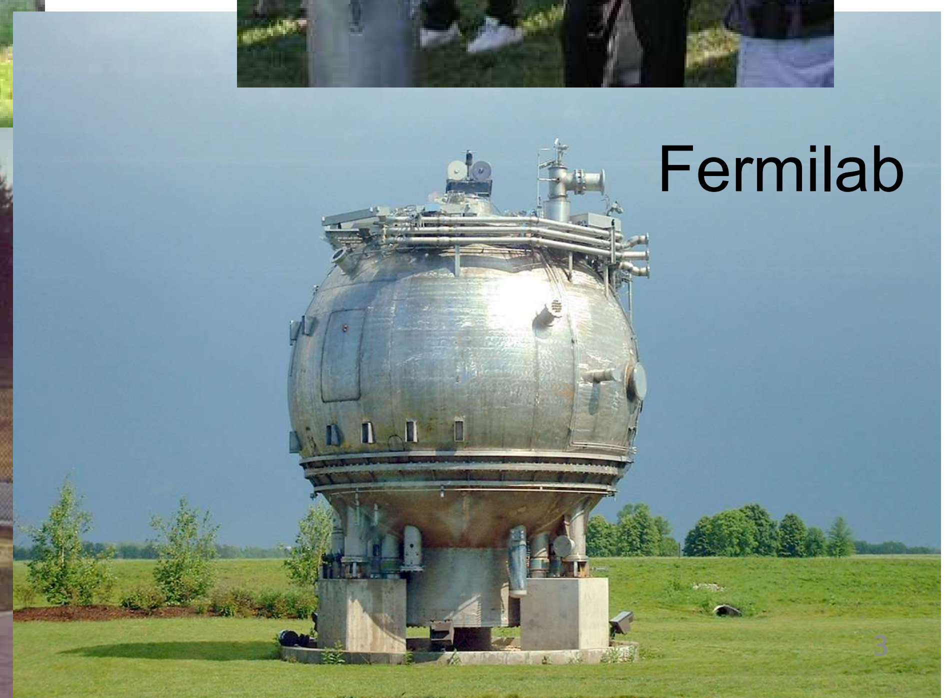
Glaser with 1-cm diameter bubble chamber, 1952.



Alvarez's 72 inch  chamber at LBL in 1959

# Bubble Chambers Since Mid- 80s: Lawn Ornaments

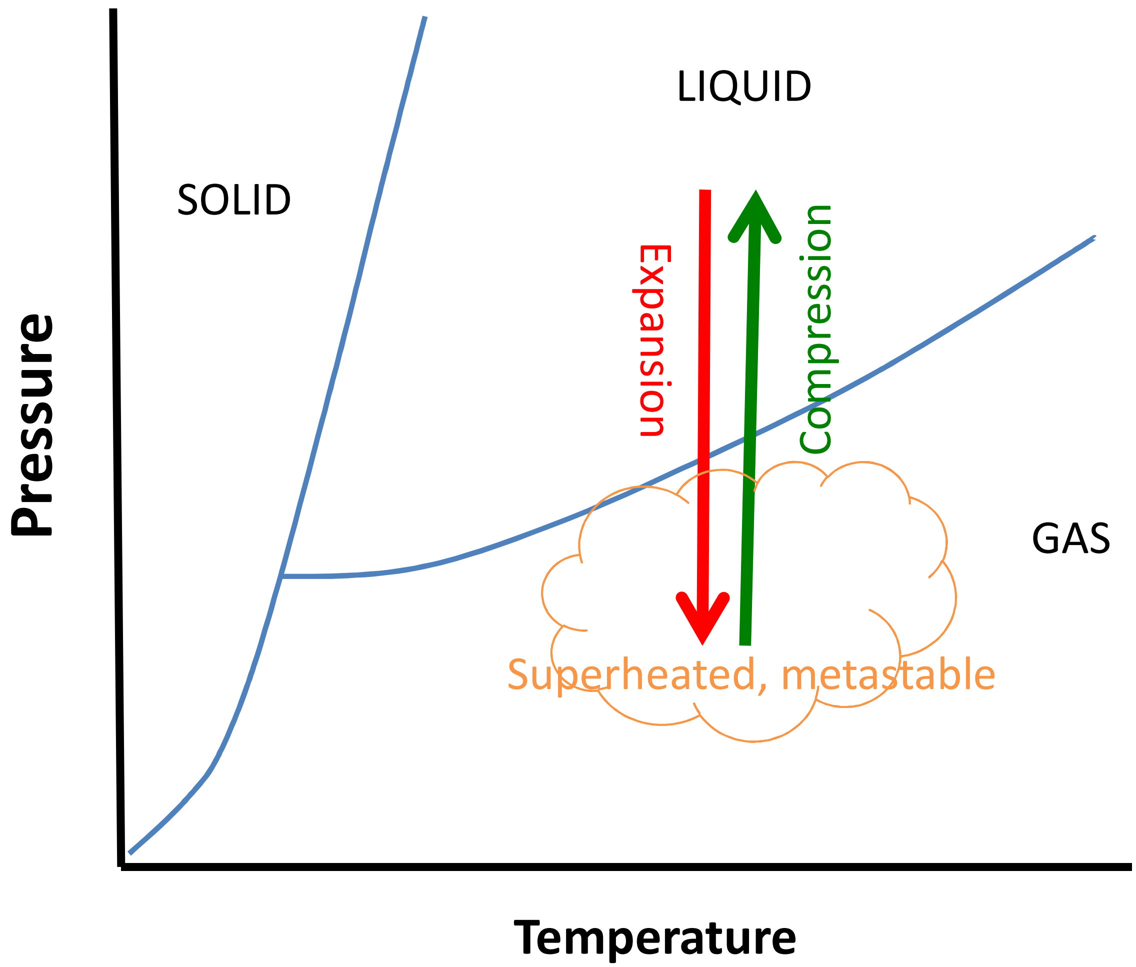


# Bubble Chambers Satisfy WIMP Detector Wish List

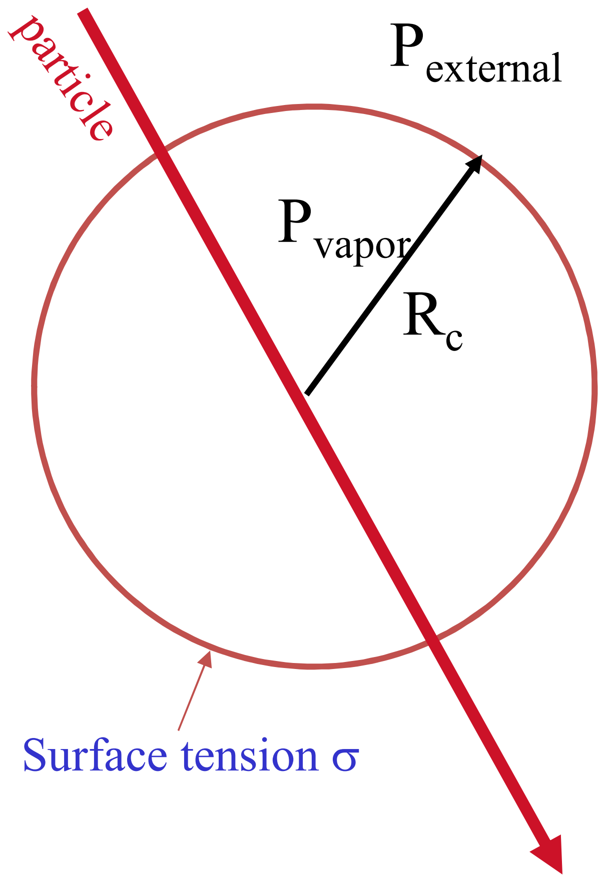
- Large target mass (>1 ton) ✔
- Low energy threshold. (~ 3 keV) ✔
- Low backgrounds from environmental radioactivity. ✔
- Multiple target nuclei- test expected cross section dependences on atomic number and nuclear spin, other nuclear effects. ✔
- Measure nuclear recoil energy distribution. Yes by varying threshold
- Measure nuclear recoil direction. Sorry

# Bubble Chamber Expansion/ Compression Cycle



# Bubble Nucleation by Radiation

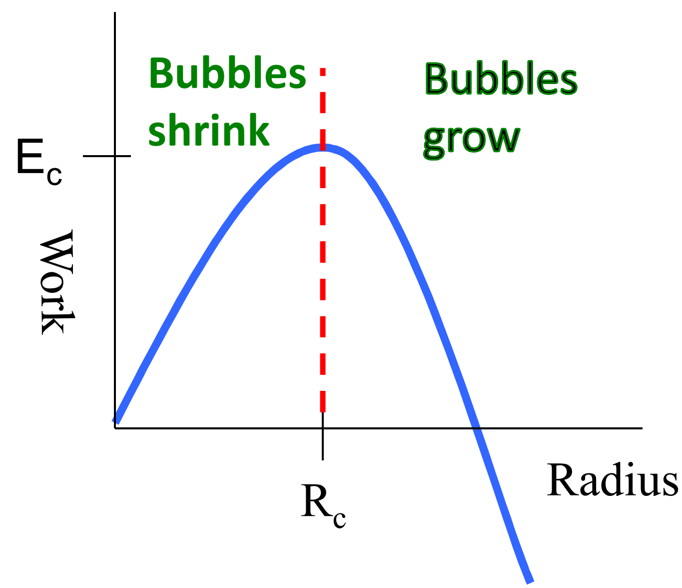
(Seitz, "Thermal Spike Model", 1957)




- Pressure inside bubble is equilibrium vapor pressure.
- At critical radius $R_c$ surface tension balances pressure.

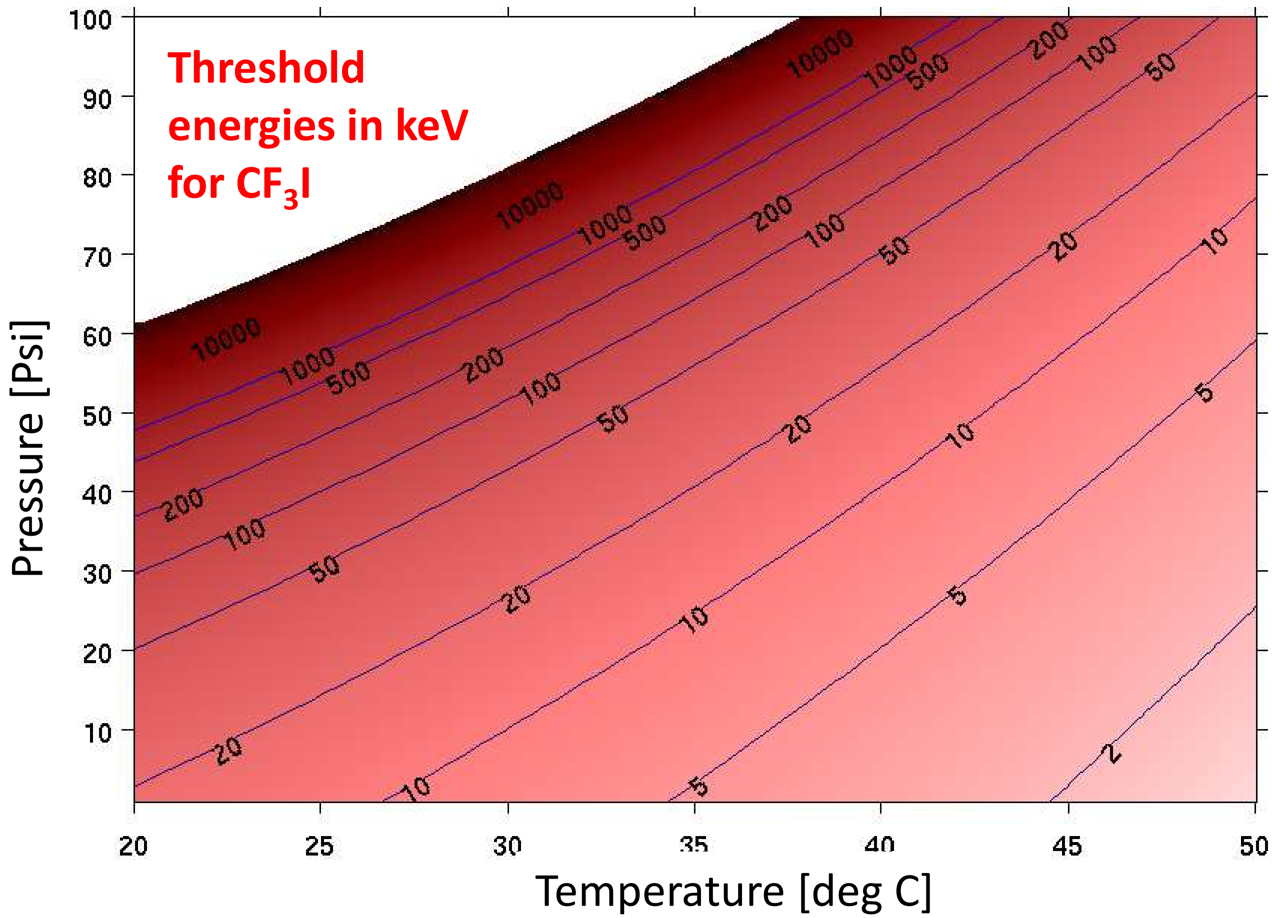
$$R_C = \frac{2\sigma}{P_{vapor} - P_{external}}$$

- Bubbles bigger than the critical radius $R_c$ will grow; smaller bubbles will shrink to zero.



# Energy Barrier to Bubble Nucleation

$$E_{th} = \underbrace{4\pi r_c^2 \left(\sigma - T\frac{\partial \sigma}{\partial T}\right)}_{\text{Surface energy}} + \underbrace{\frac{4}{3}\pi r_c^3 \rho_v h}_{\text{Latent heat}}$$

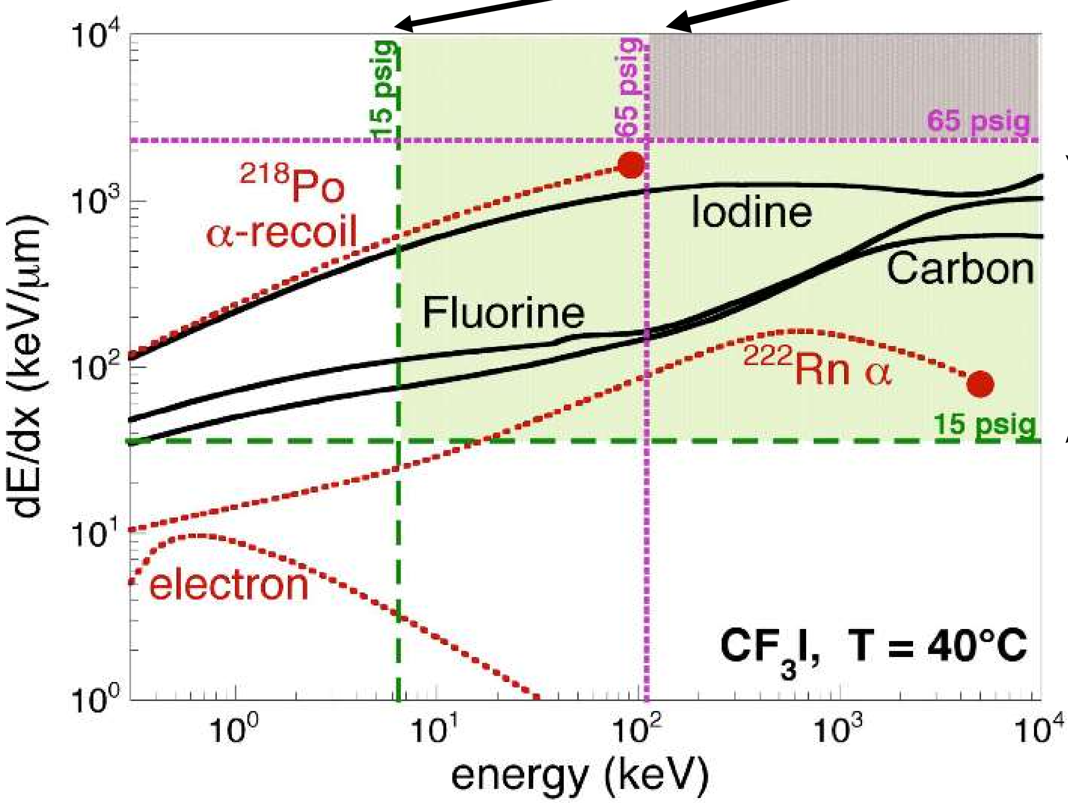



Robinson thesis 2015

# Tuning the dE/dX Threshold for Bubble Nucleation

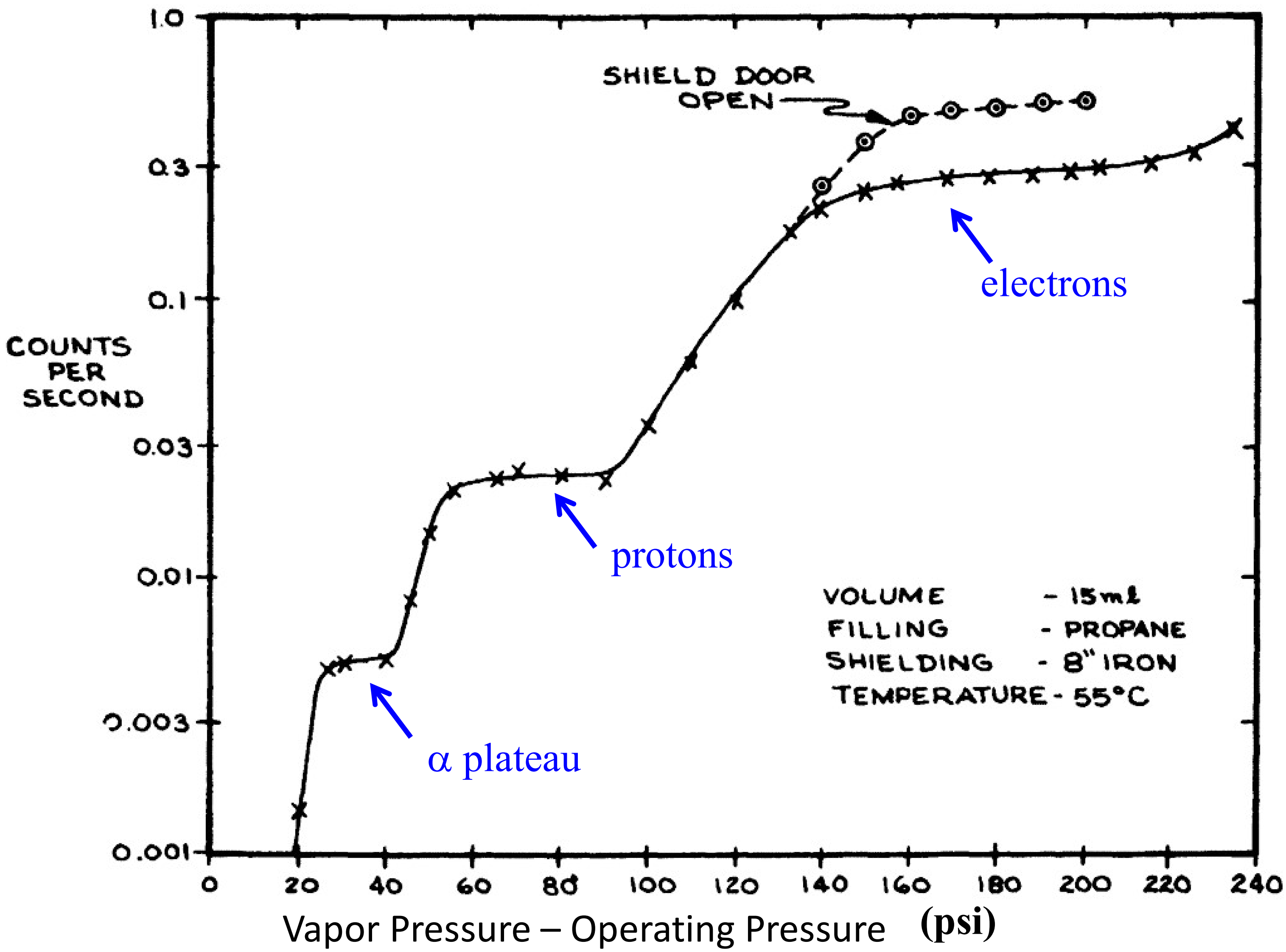
- The bubble chamber operator chooses a pressure and temperature, fixing the minimum size of bubbles that are allowed to grow against surface tension.
- This simultaneously determines minimum deposited energy and energy loss density (dE/dX) that will nucleate bubbles.
- Example below: superheated $CF_3I$ at fixed temperature, two operating pressures.

Energy Thresholds




dE/dX threshold at 15 psi and 65 psi

# dE/dX Discrimination in 1960's Bubble Chambers

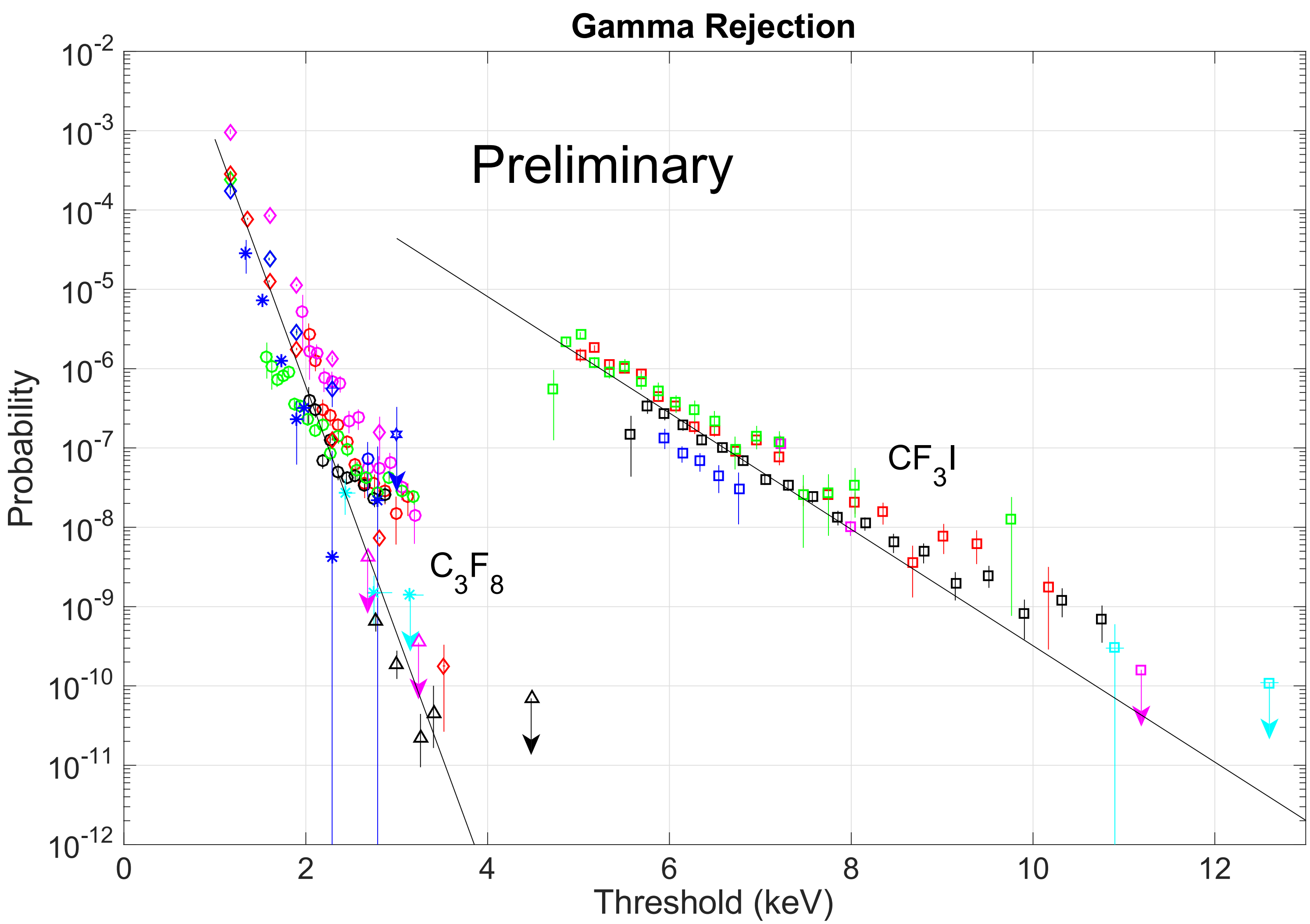




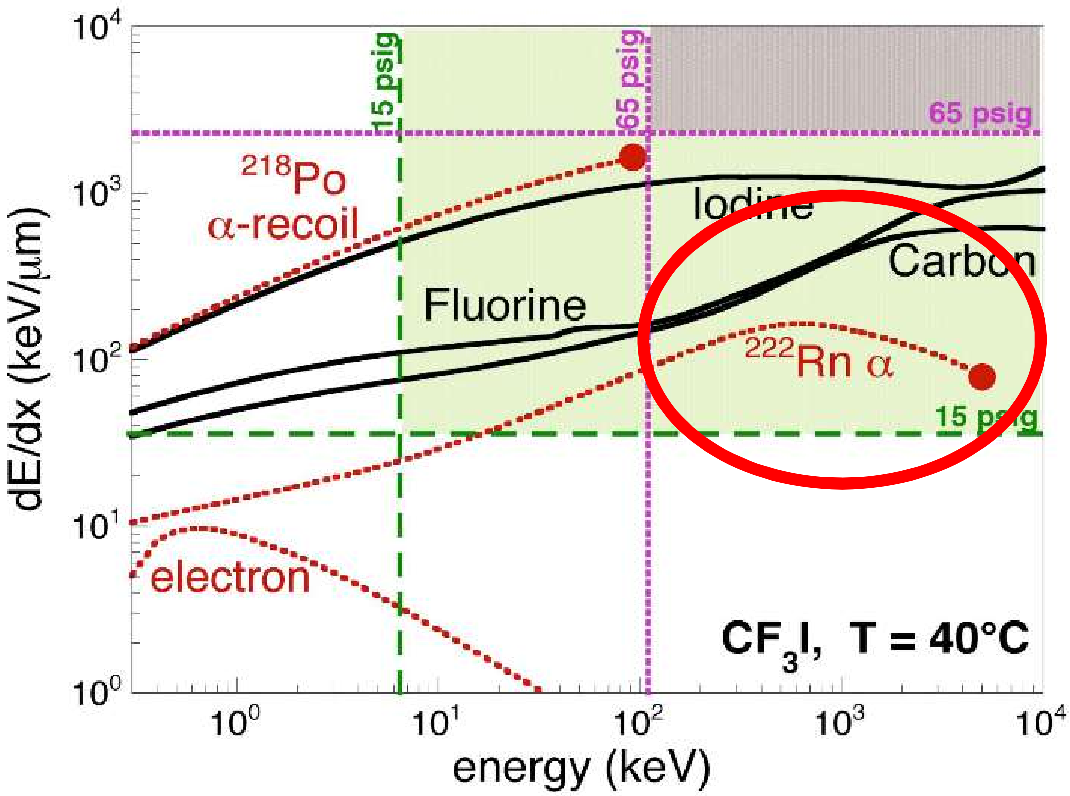

Waters, Petroff, and Koski, IEEE Trans. Nuc. Sci. 16(1) 398-401 (1969)

# Gamma Insensitivity: Current Data

Bubble nucleation probability for a gamma interaction in $C_3F_8$ or $CF_3I$



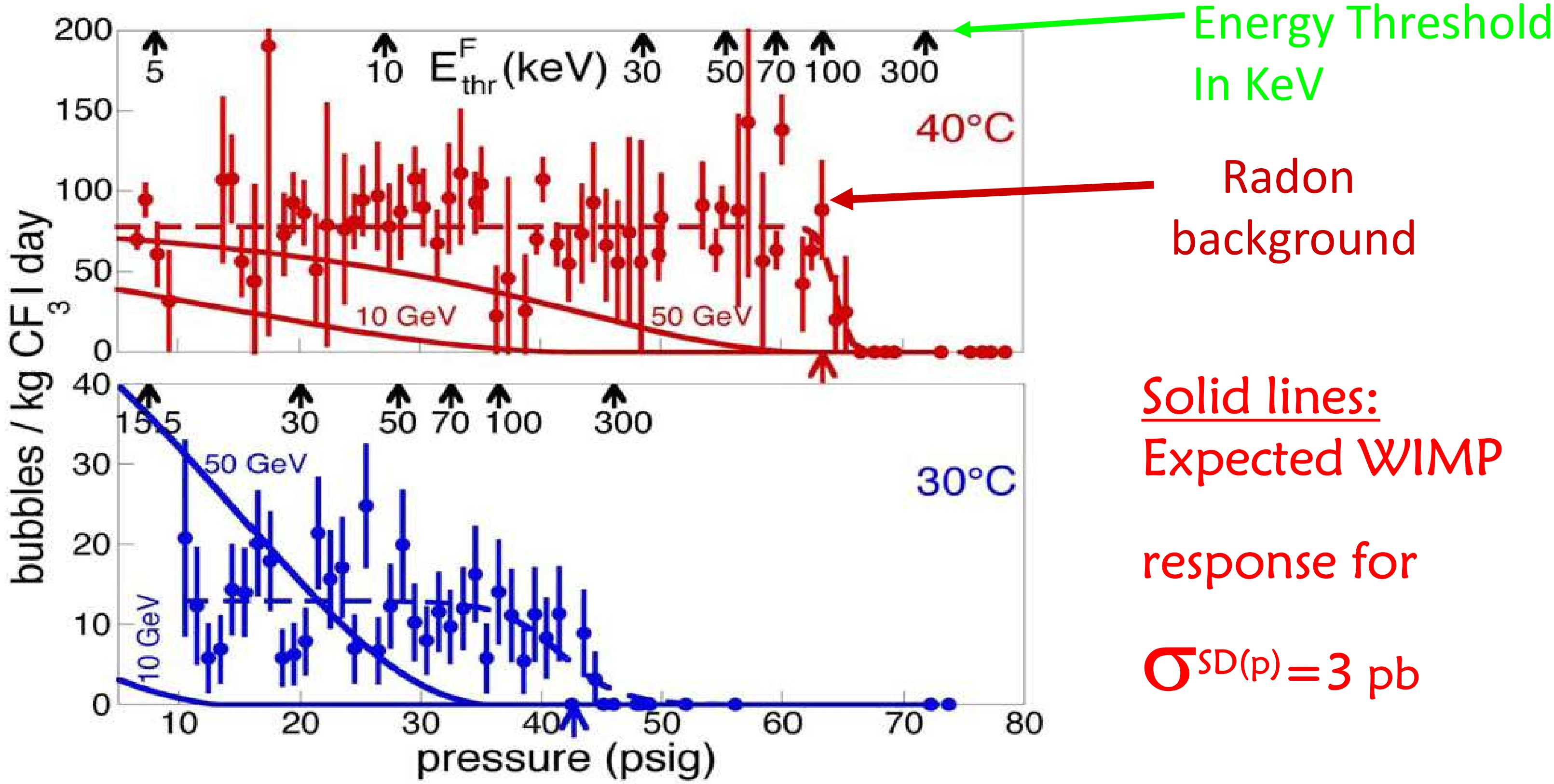
# Alpha Decay Backgrounds




- Alpha particles and recoiling daughter nuclei can nucleate bubbles.
- The $^{238}$U and $^{232}$Th decay series include many alpha emitters, including radon ($^{222}$Rn) and its daughters, which are ubiquitous in the environment.
- Reduced to <1 event/ ton-day in solar neutrino experiments (Borexino, SNO) by distillation and other chemical purification techniques.

# Alpha Backgrounds in 2006 COUPP Run

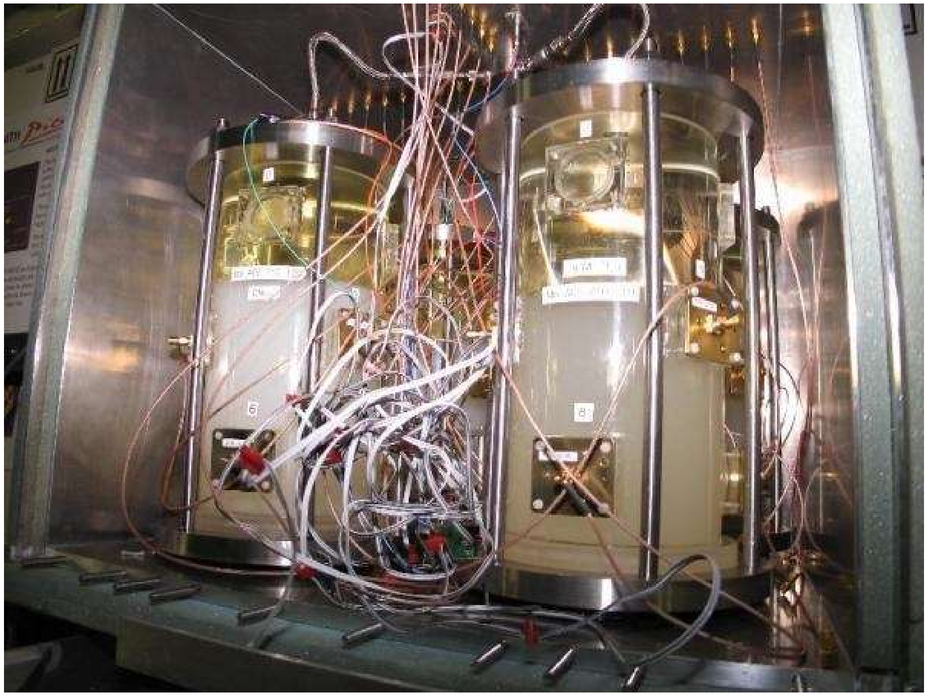
- High alpha background rate from radon (O-ring emanation).
- Used pressure scanning to separate WIMPs/ Alphas on basis of energy spectrum.

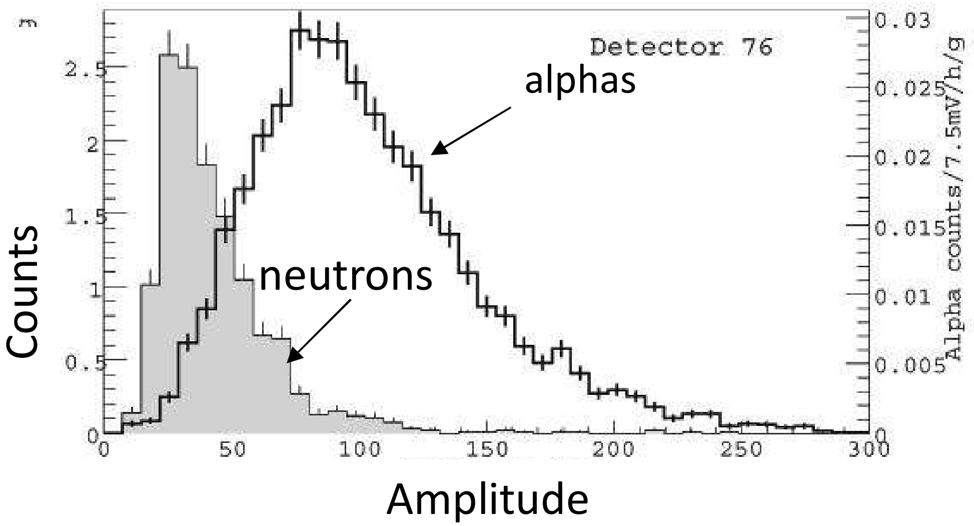



Solid lines:
Expected WIMP
response for
$\sigma^{SD(p)} = 3$ pb

# PICASSO Discovery of Alpha Discrimination Using Sound Waves (2008)

- Bubble nucleation detected acoustically using piezoelectric microphones.
- Amplitude of acoustic signal differs for Alphas vs. Nuclear recoils.
- Distributions overlap at the ~10% level.

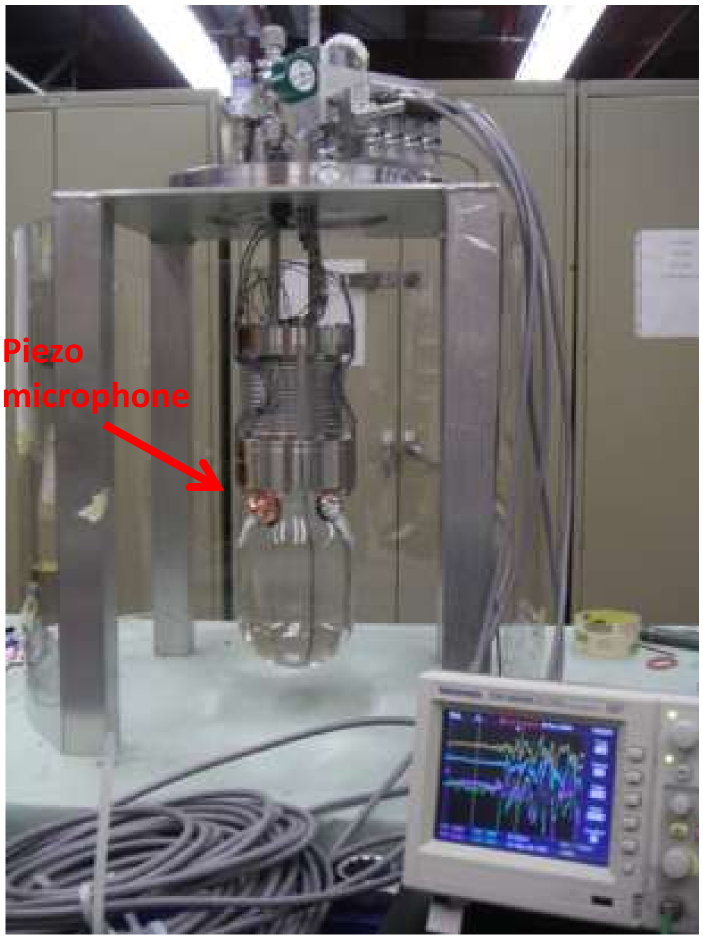


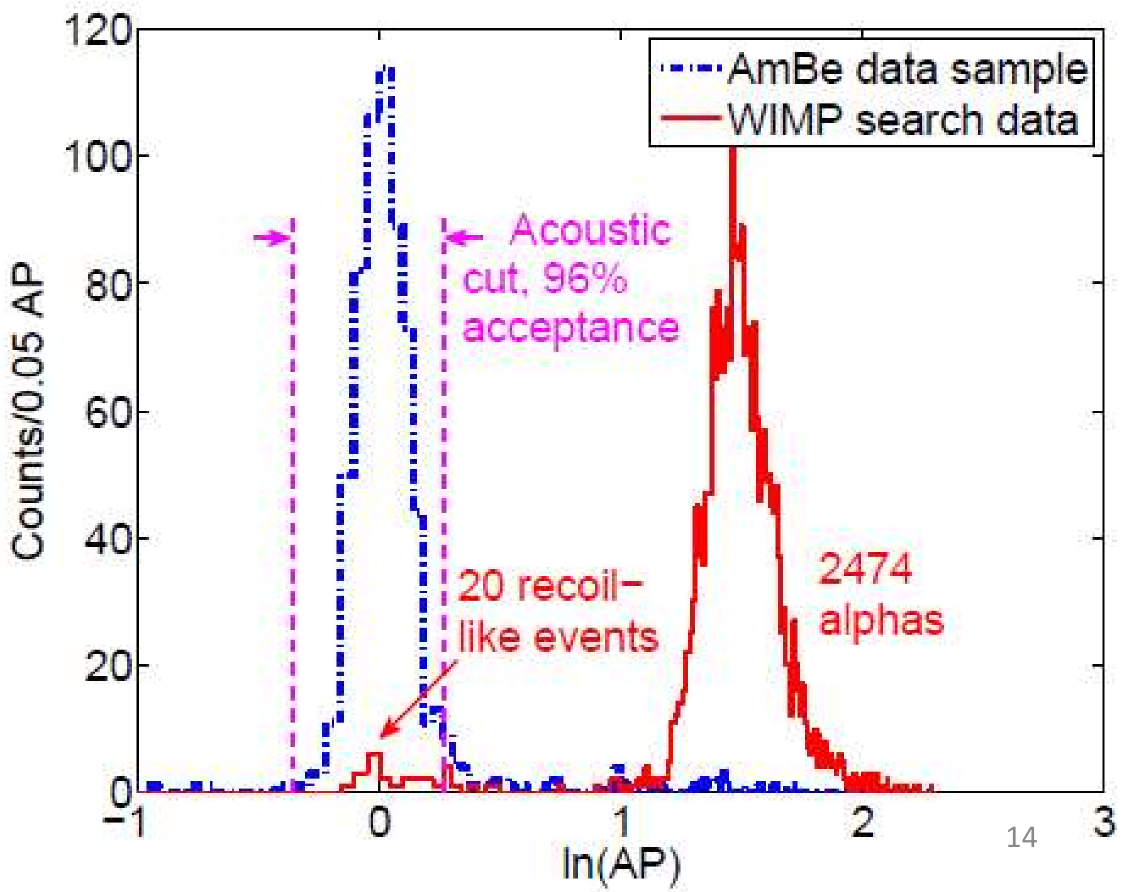



New Journal of Physics arXiv:0807.1536

# Acoustic Particle ID in Bubble Chambers

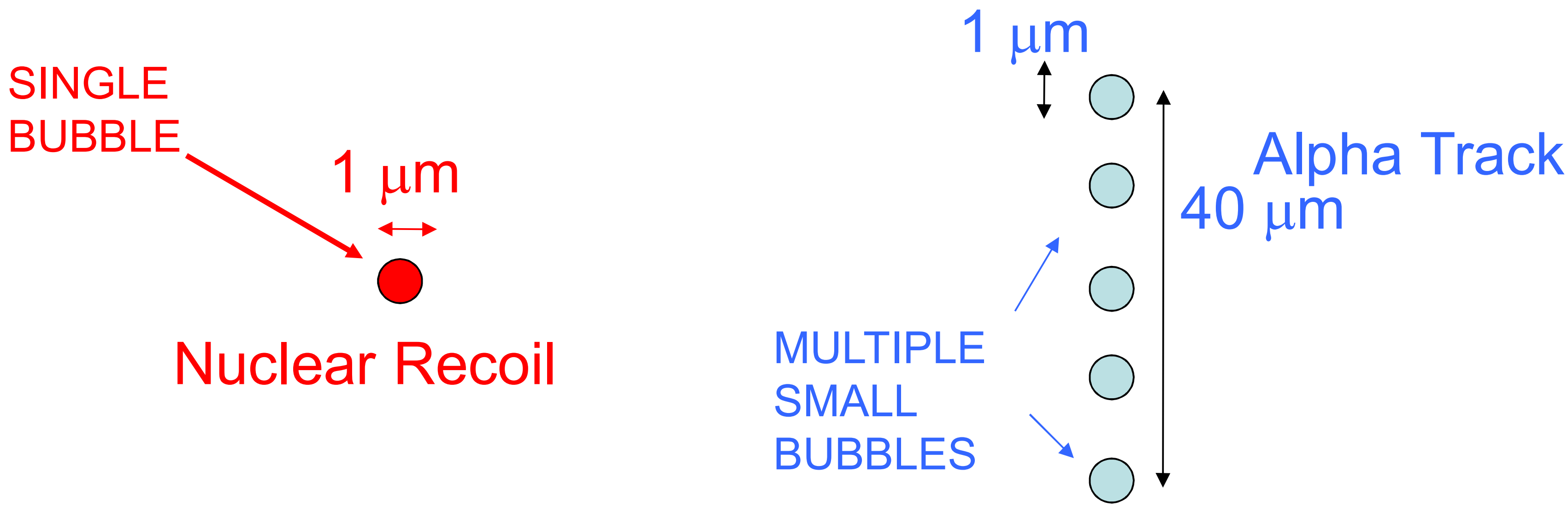
• Works much better in bubble chambers than in droplet detectors.
• >99.3% of alpha background rejected with 96% signal acceptance.



# Discrimination Between Alpha Decay Bubbles and Nuclear Recoils?

*Imagine that we could photograph the bubble track with micron resolution a few microseconds after nucleation occurs, while bubbles are still just ~ 1 micron in diameter.*




*Video imaging of events on these time and distance scales impossible over the large required field of view: e.g. ~ 1 $m^3$ of volume with ~1 micron resolution at a video rate of ~1 MHz.*

*<u>but</u>*

*Acoustic signal from alpha track is several times louder than recoil signal at high frequencies due to presence of multiple radiating bubbles.*

# PICO

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE
I. Lawson

UNIVERSITAT POLITÈCNICA DE VALÈNCIA
M. Ardid, M. Bou-Cabo, I. Felis

NORTHWESTERN UNIVERSITY
D. Baxter, C.E. Dahl, M. Jin, J. Zhang

P. Bhattacharjee. M. Das, S. Seth

CZECH TECHNICAL UNIVERSITY IN PRAGUE
R. Filgas, I. Stekl

Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO
J.I. Collar, A.E. Robinson

INDIANA UNIVERSITY SOUTH BEND
E. Behnke, H. Borsodi, O. Harris, A. LeClair, I. Levine, E. Mann, J. Wells

Université de Montréal
F. Debris, M. Fines-Neuschild, F. Girard, C.M. Jackson, M. Lafrenière, M. Laurin, J.-P. Martin, A. Plante, N. Starinski, V. Zacek

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S.J. Brice, D. Broemmelsiek, P.S. Cooper, M. Crisler, W.H. Lippincott, E. Ramberg, M.K. Ruschman, A. Sonnenschein

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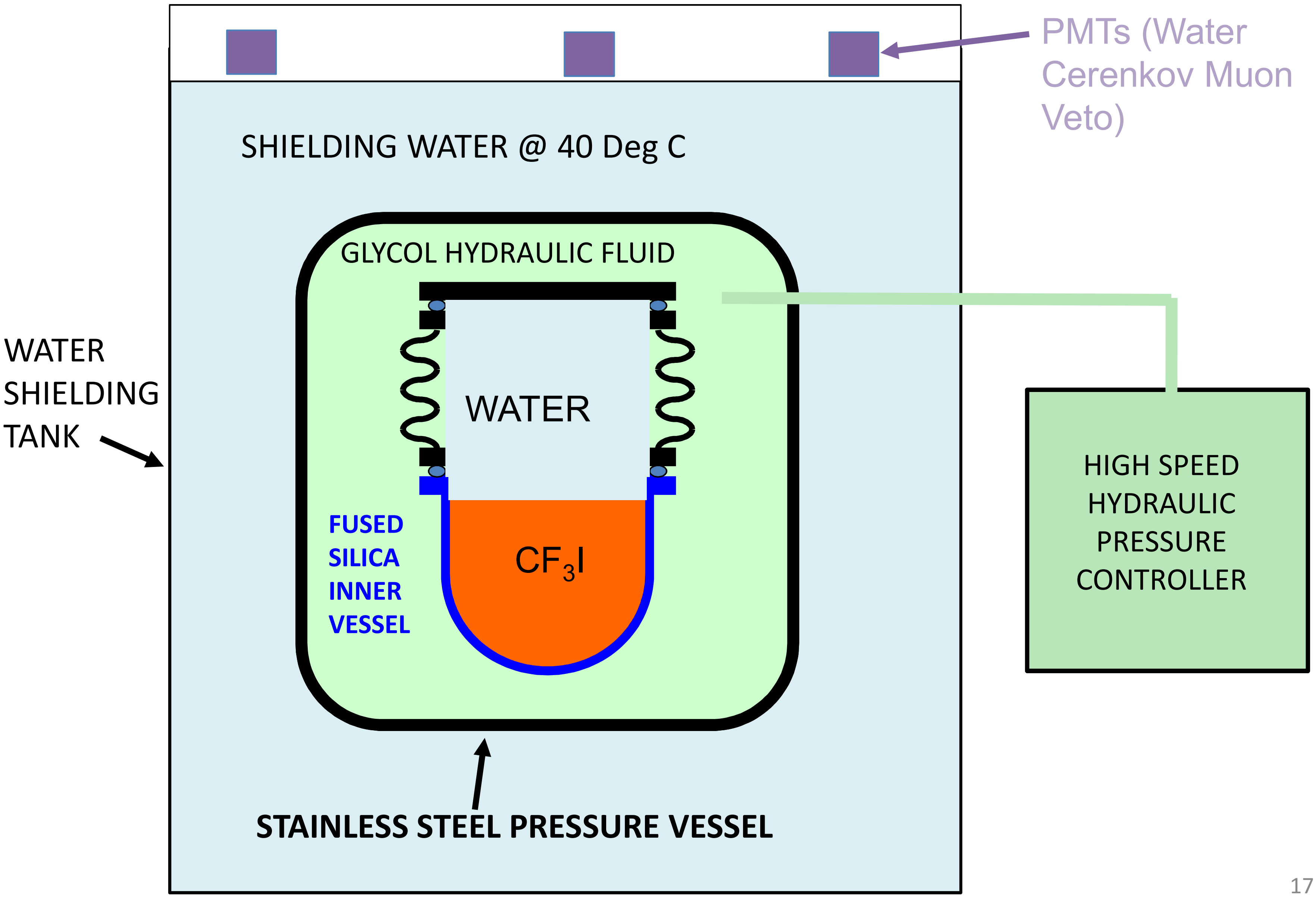
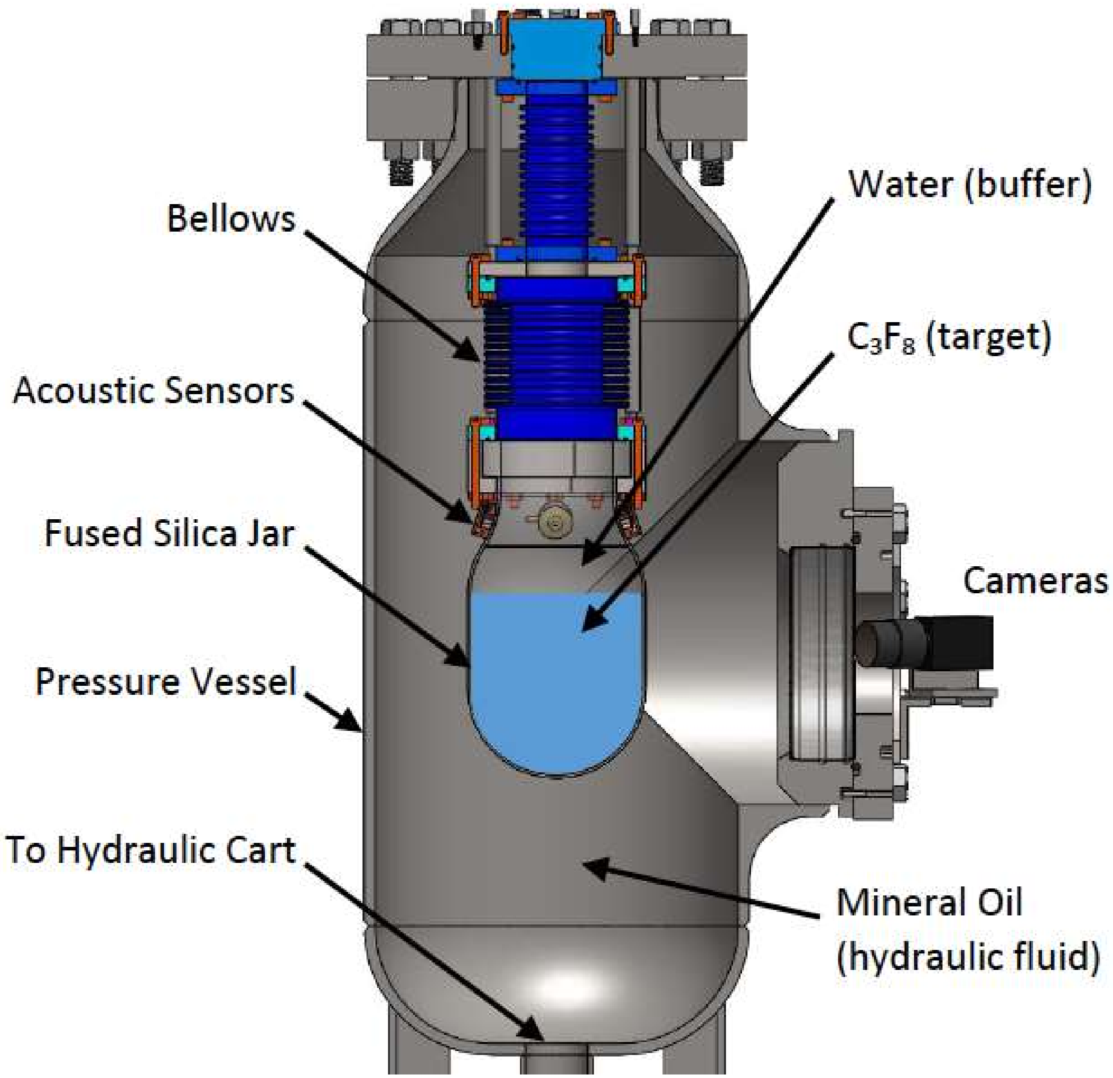
UNIVERSITY OF TORONTO
K. Clark

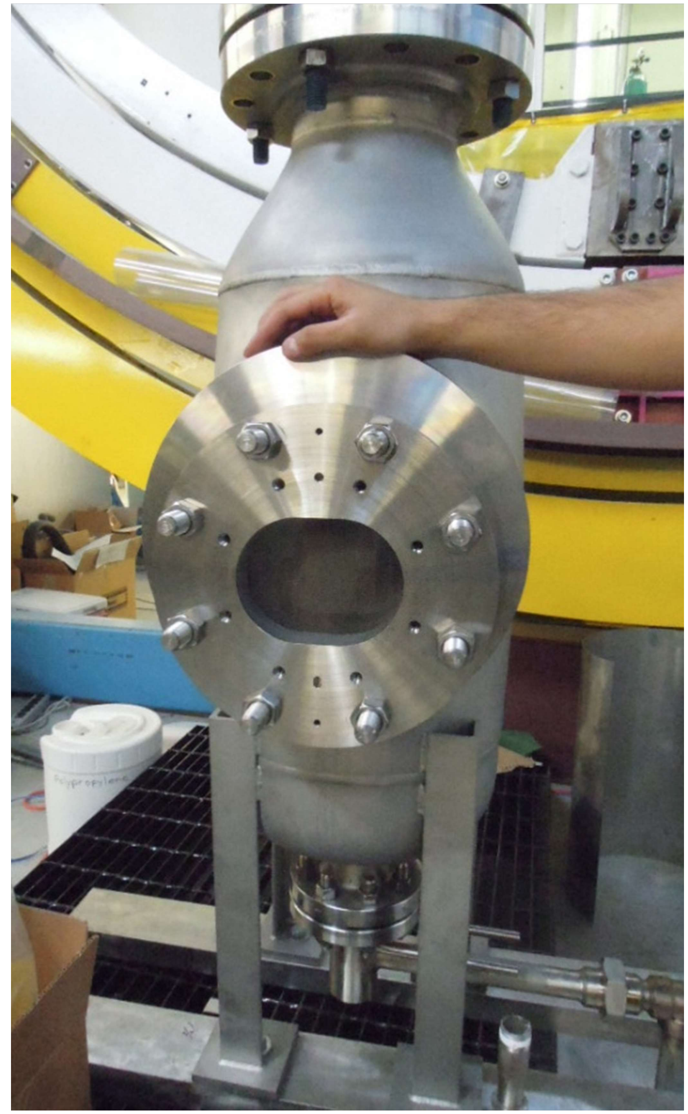
LaurentianUniversity UniversitéLaurentienne
J. Farine, A. Le Blanc, R. Podviyanuk, O. Scallon, U. Wichoski

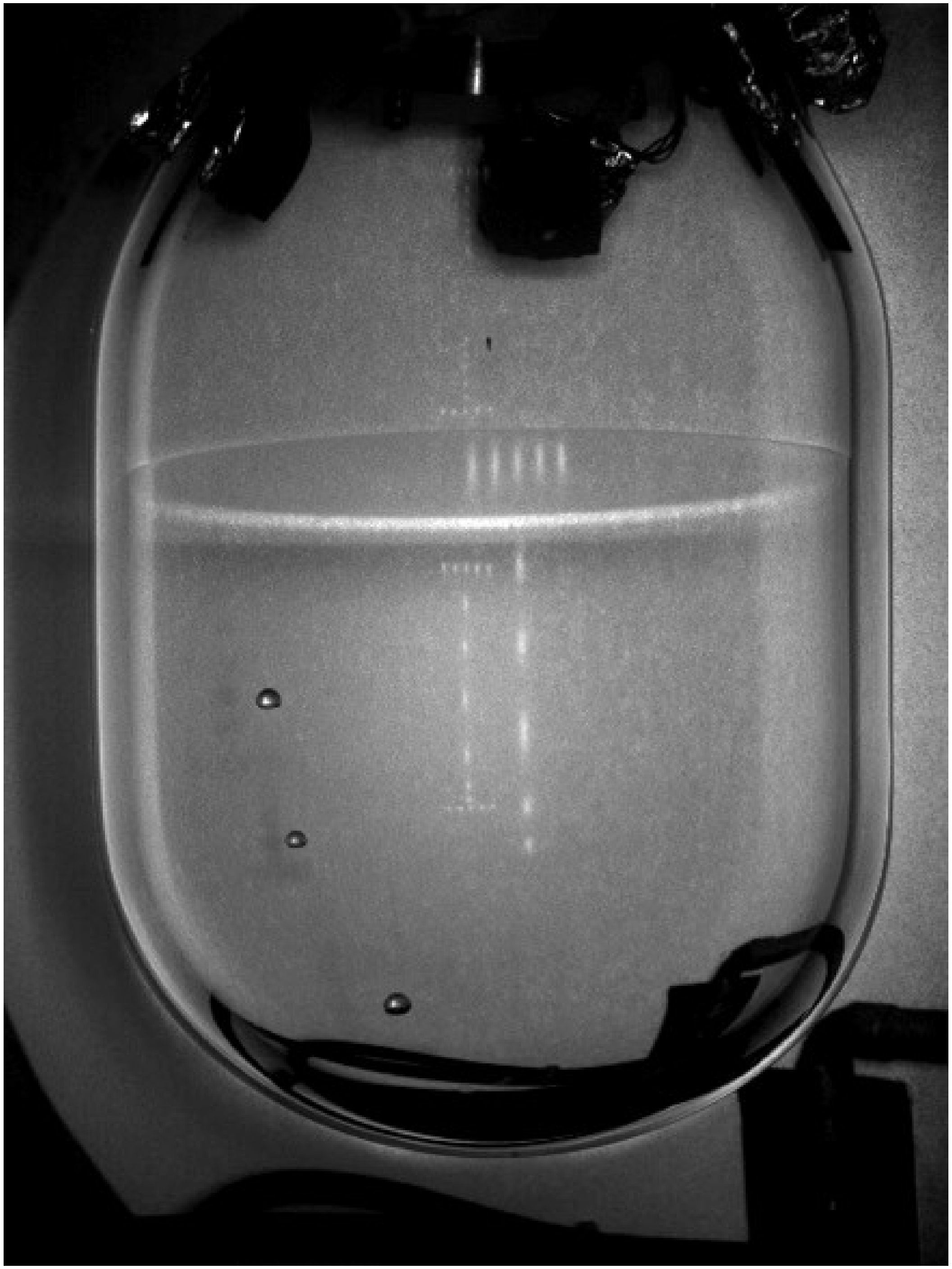
# Large Bubble Chamber WIMP Detector Cartoon



# 2-Liter Chamber : PICO-2L



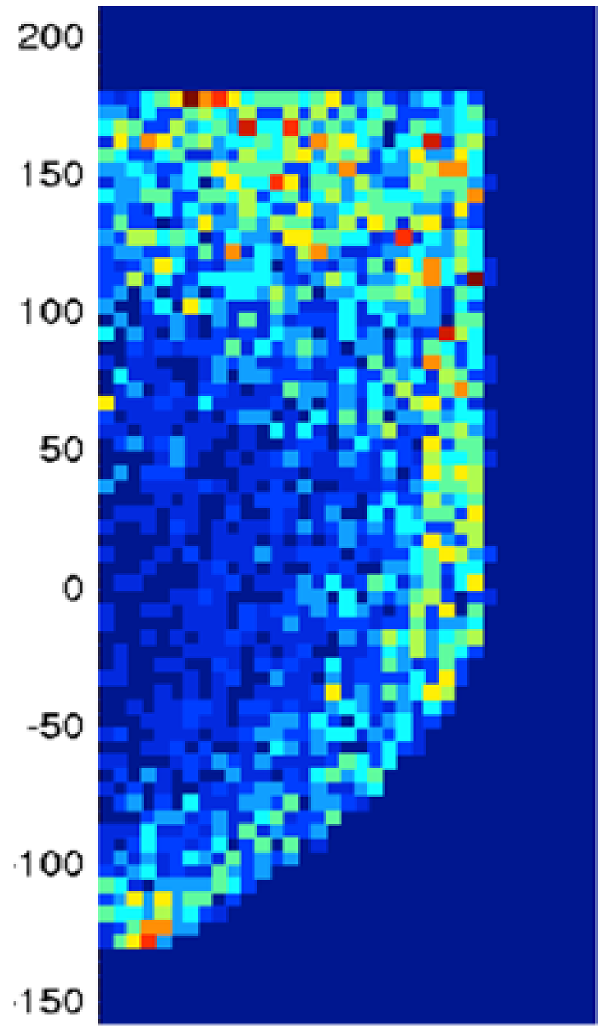





# PICO-60 at SNOLAB, 2012

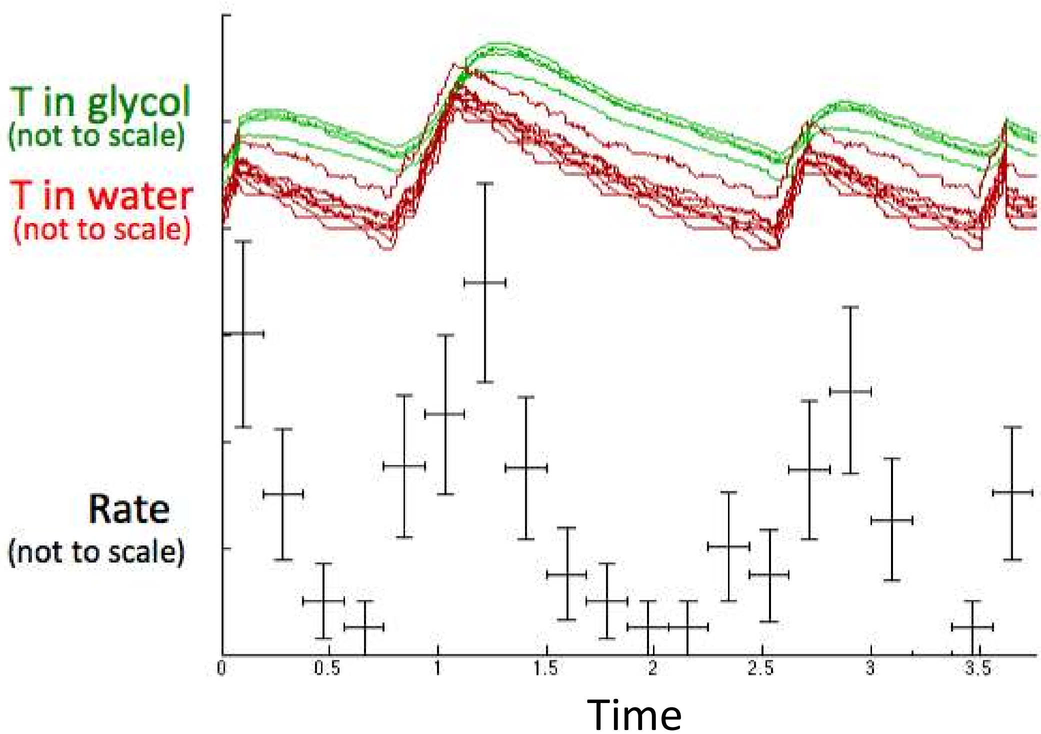
# Anomalous Background Events in 2013-2014 Run

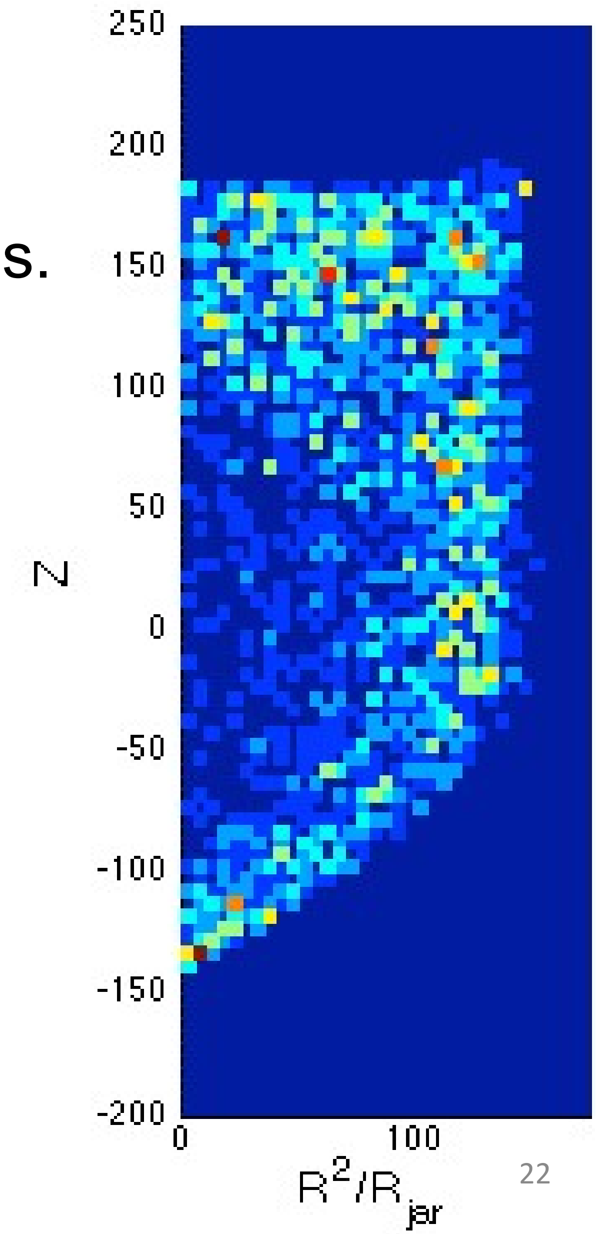
- Fluctuating rate of background events, from ~10-100 counts per day.
- Non-uniform spatial distribution, with highest rates near top and walls of chamber.
- Highest rates during periods of temperature instability.
- Highest rates at beginning of bubble chamber expansion cycle.
- Anomalous acoustic amplitude distribution.



# Space and Time Distribution of Recoil-Like Events

- Acoustically identified recoil-like events have anomalous spatial and time distributions.
- Correlation with temperature changes.
- This cannot be dark matter.





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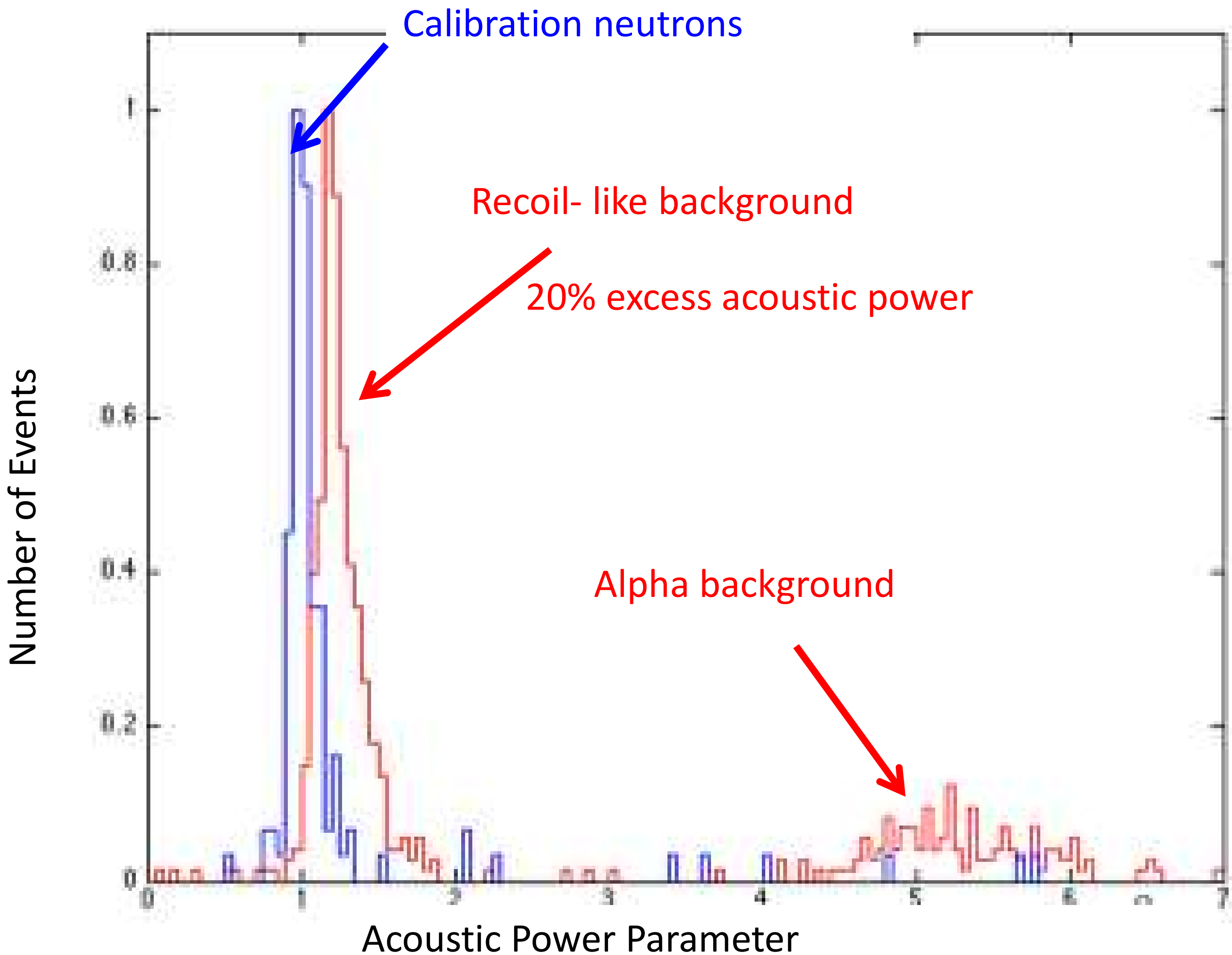
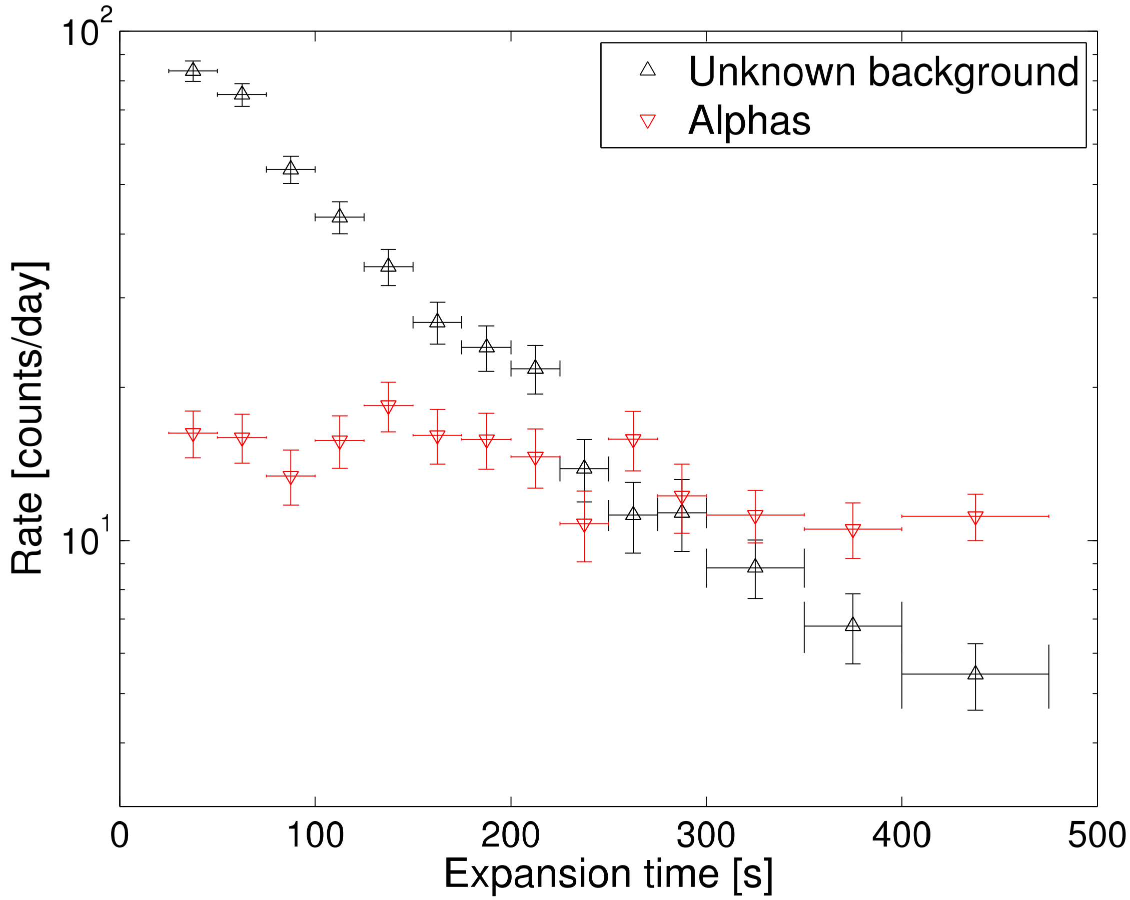
# Acoustic Distribution



# Expansion Time Dependence

- Probability of seeing a background event decreases the longer the chamber is expanded.

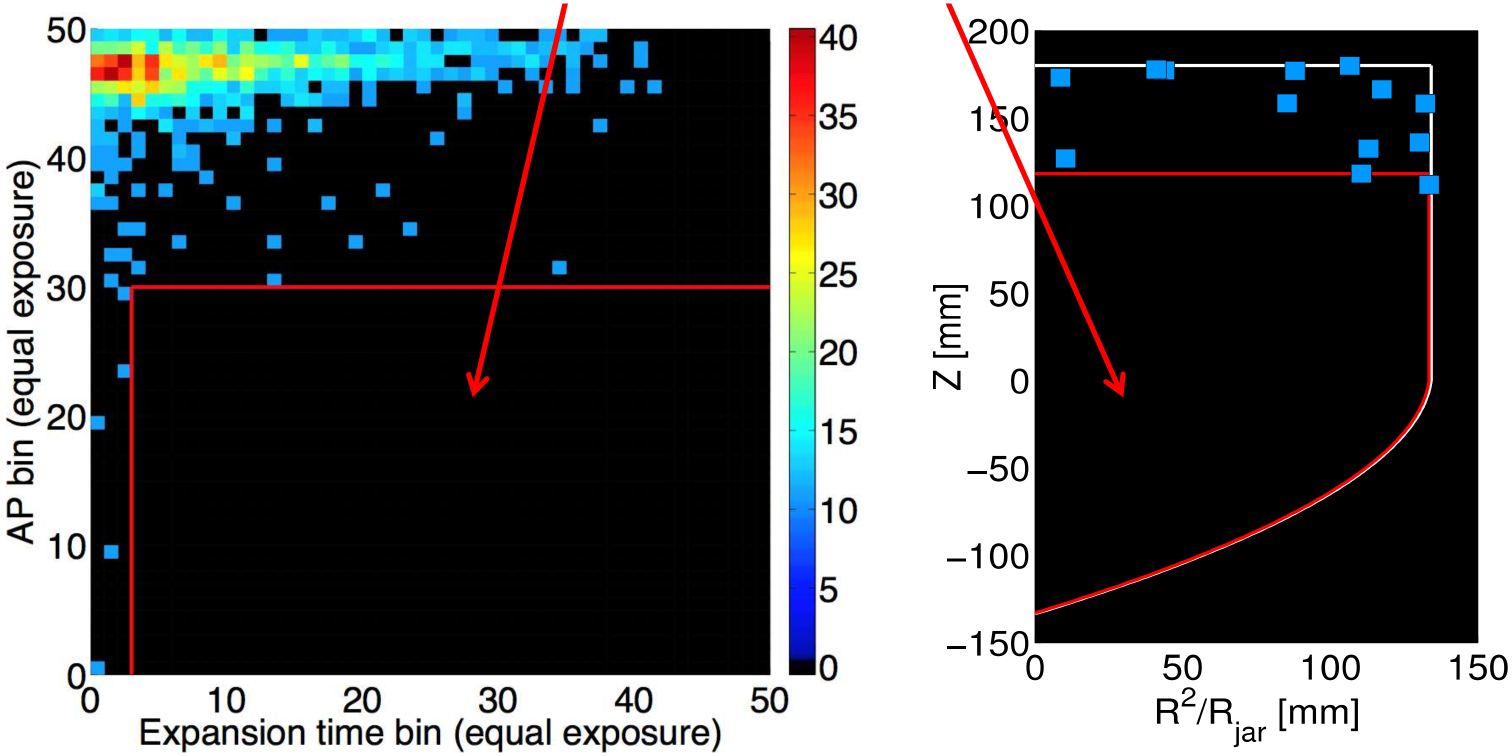


# Optimization of Cuts

- Combined cuts on position, expansion time and acoustic amplitude yield background free region.
- Monte Carlo methods used to estimate penalty for setting cuts.

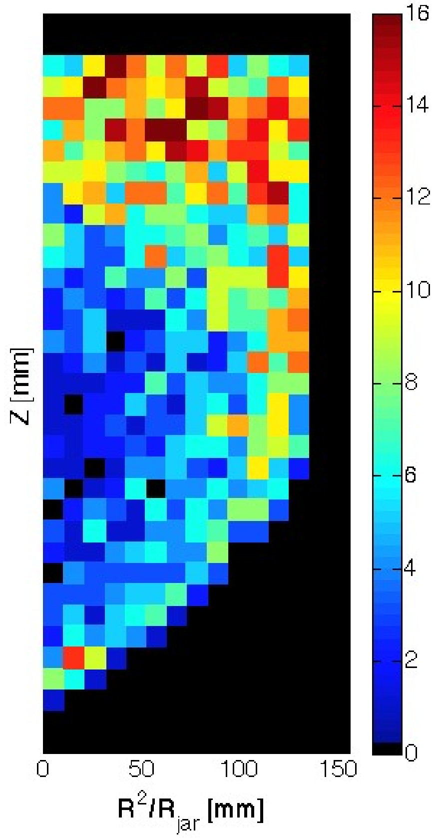
C. Amole, *et al.*, Phys. Rev. D 93, 052014 (2016)

A background free region (~50% of exposure)
by cutting on AP, expansion time, and Z

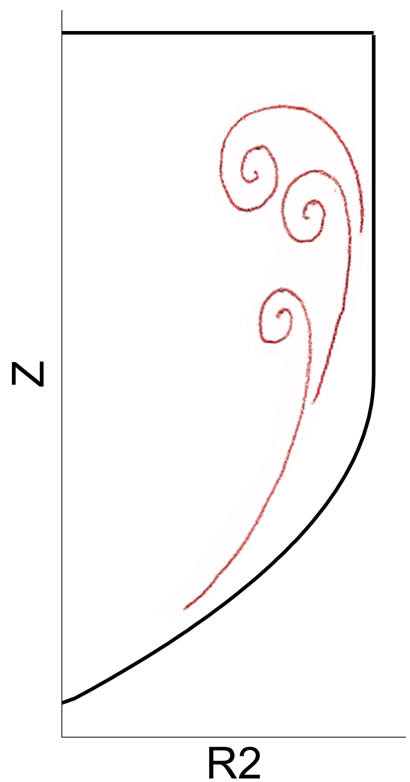


# Something Floating in the Detector?

- PICO bubbles chambers contain repeatedly stressed mechanical parts (steel and quartz) in contact with fluids → generation and transportation of particulates?




?

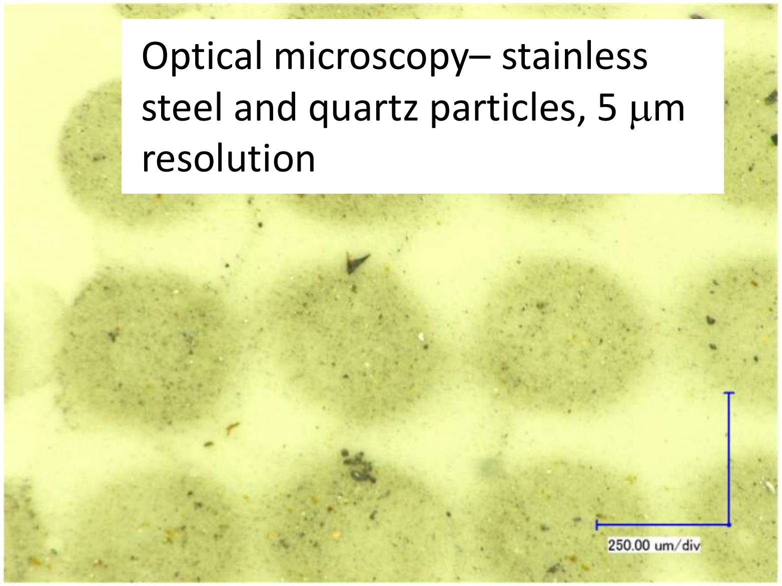



Convection stirring up particulates?

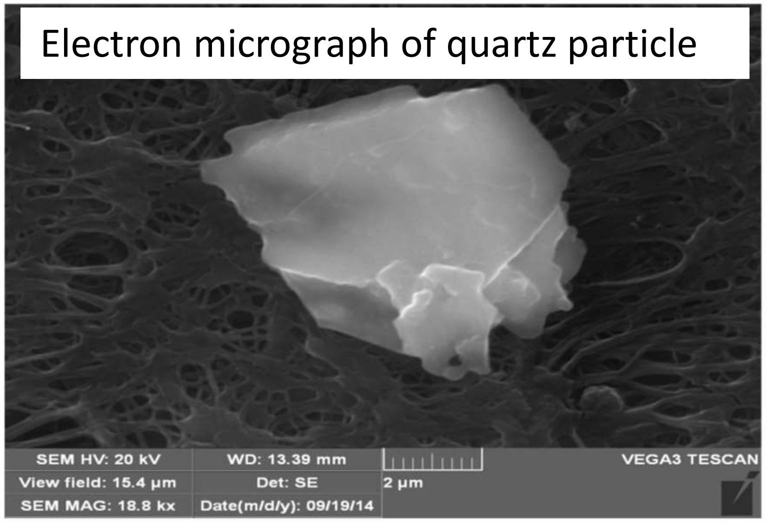
# Looking for Dust with Microscopes

- Liquids passed through PTFE filters with 200 nm pore size.
- Studied using optical and electron microscopy, X-ray fluorescence, Alpha spectroscopy, mass spectroscopy at PNNL and University of Alberta.
- Result: majority of contamination from quartz and stainless steel materials used in chamber construction.

- PICO-60 sample:
  - 7 μg quartz particles
  - 240 μg stainless steel and iron oxide




Optical microscopy– stainless steel and quartz particles, 5 μm resolution

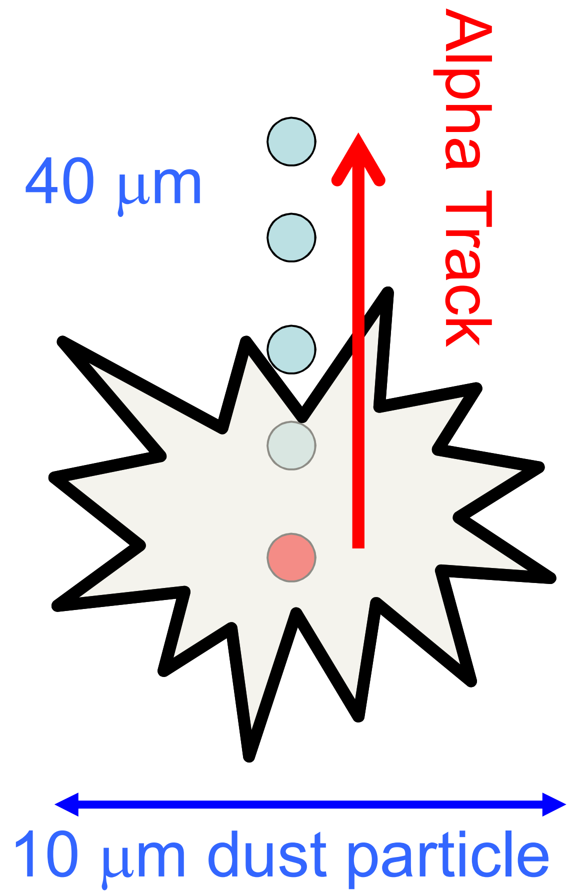



Electron micrograph of quartz particle

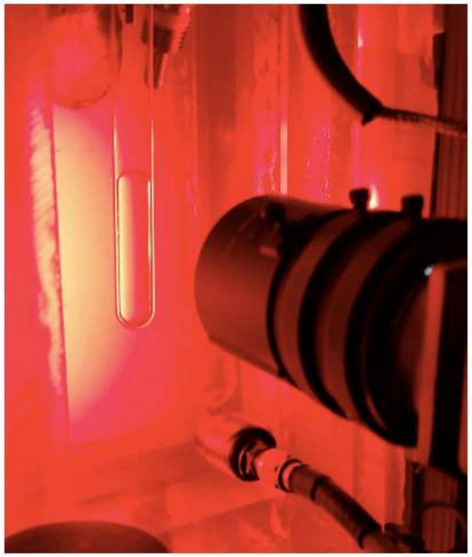
# Possible Mechanism for Generating Events- Embedded Alpha Emitters

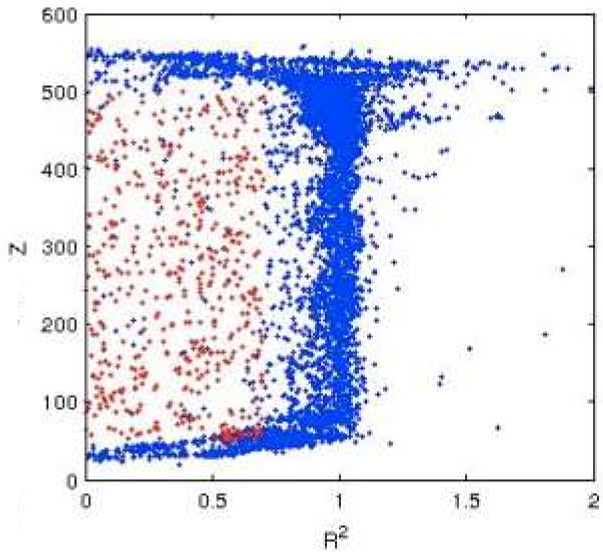
- When an alpha decay occurs in liquid, alpha particle and daughter nucleus recoil contribute about equally to amplitude of acoustic signal → alpha decay acoustic amplitude approximately 2 x nuclear recoil from a neutron or WIMP.

- If the alpha-emitting isotope is embedded in solid material <10 microns thick, alpha particle can escape to make a bubble, but nuclear recoil is hidden in the solid. Acoustic amplitude similar to nuclear recoil.



# Investigating radioactive particulate





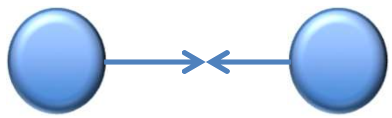

Radioactive particulate injected into a test chamber operated at Queen's University settles on the walls and liquid interface.

NO measurable increase in low-AP bulk rate.

Fine silica powder strongly prefers to stay in the water buffer fluid above the active fluid.

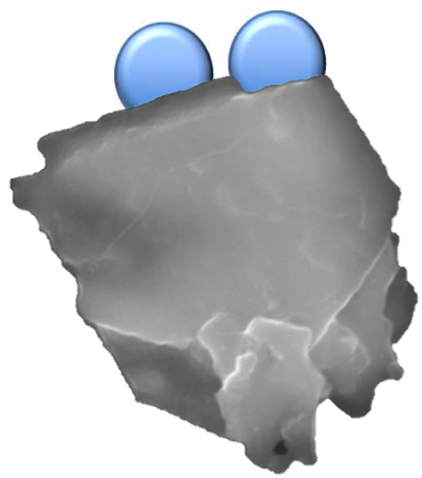
# Bubble nucleation by surface tension

Merging of two water droplets releases O(1 keV) of surface tension energy.



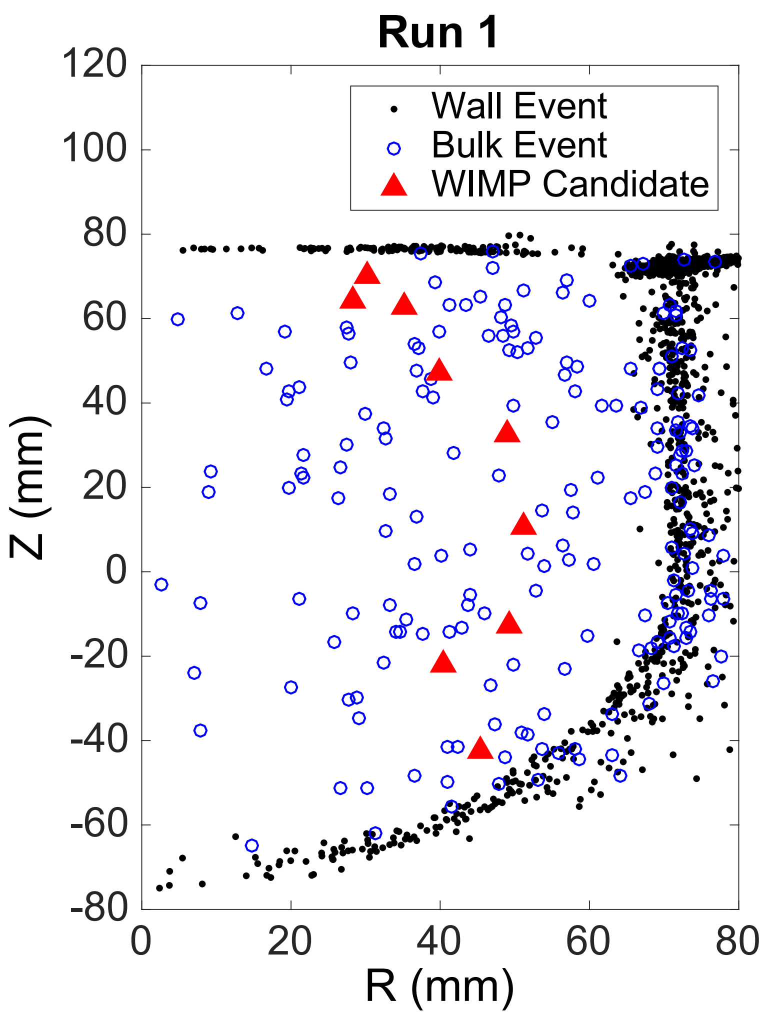
The water lowers the bubble nucleation threshold, so the released energy can nucleate bubbles at PICO operating thresholds of a few keV.

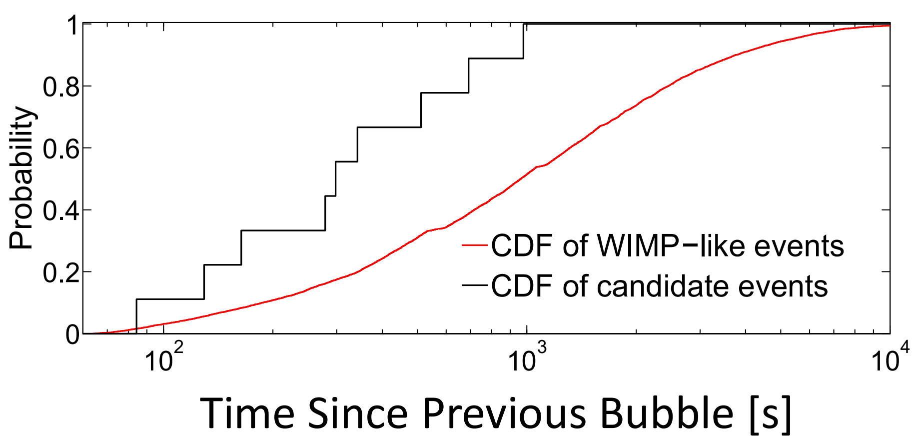
The merging water droplets could be attached to solid particulate.



# PICO-2L 2013-2014 Run

- Smaller PICO-2L chamber running with $C_3F_8$ and low threshold (3.2 keV).
- Better sensitivity to lighter WIMPs.
- Lower backgrounds: 9 background events in 32 live days at 3.2 keV.
- Time correlations with previous expansions.

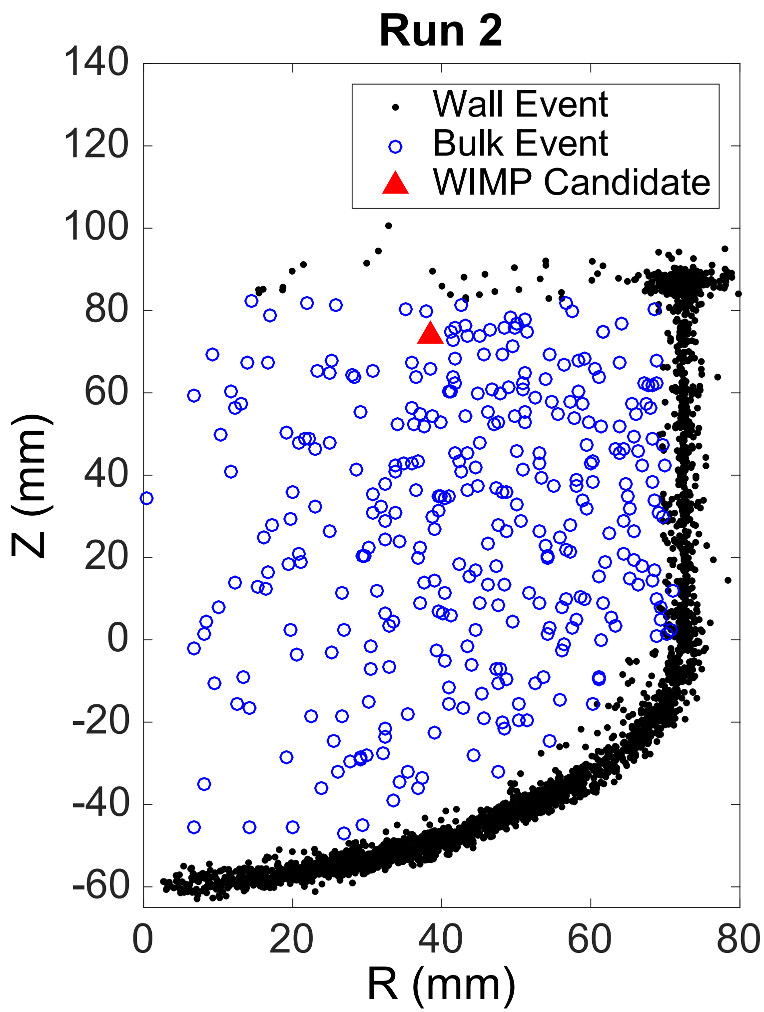



PRL 114 231302

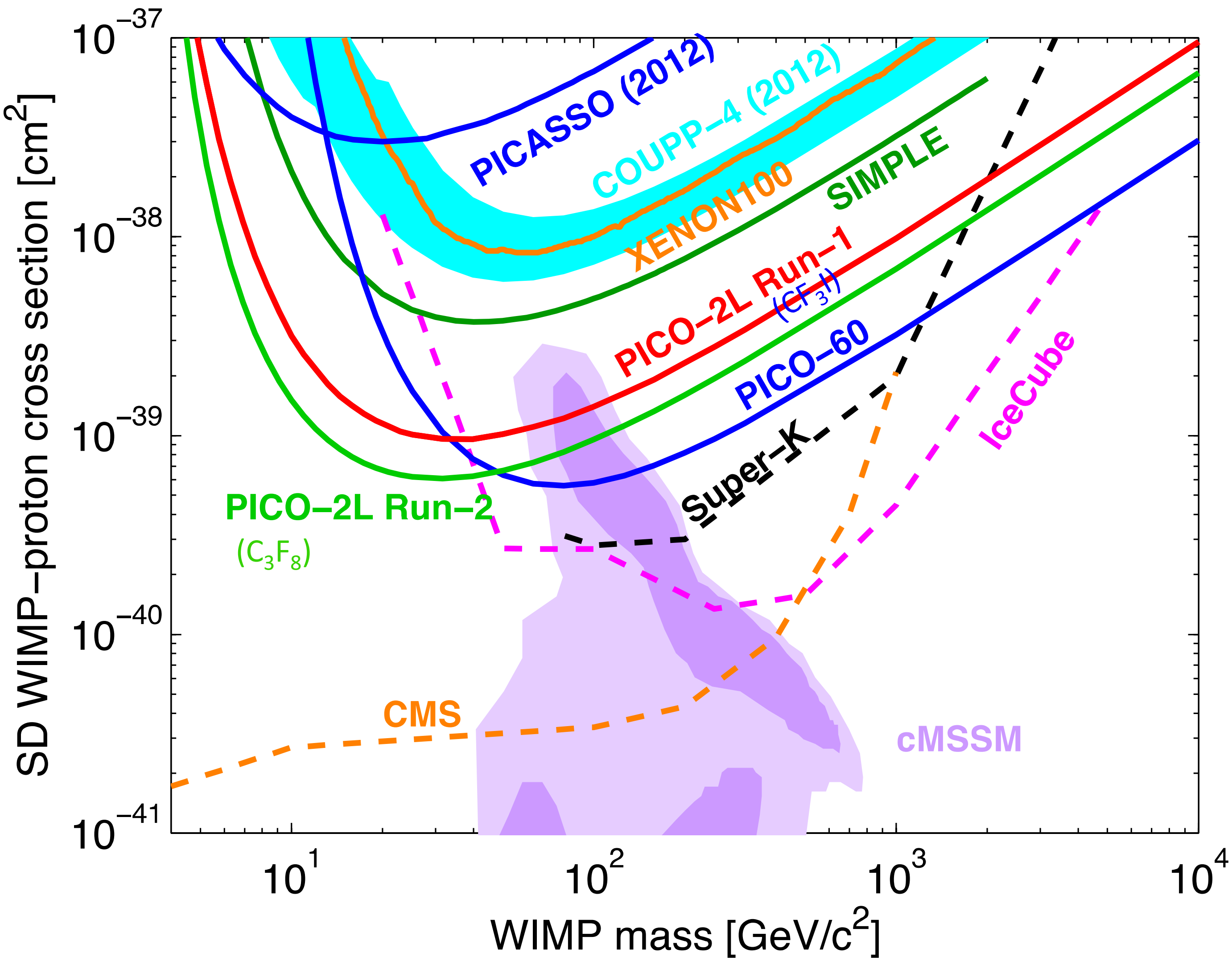
# PICO-2L 2015 Run

- Improved cleaning and assembly procedures.
- One recoil-like event in 66 live days at 3.2 keV threshold, *consistent with estimated neutron rate.*
- Anomalous background reduced by at least an order of magnitude with respect to previous run at same threshold.

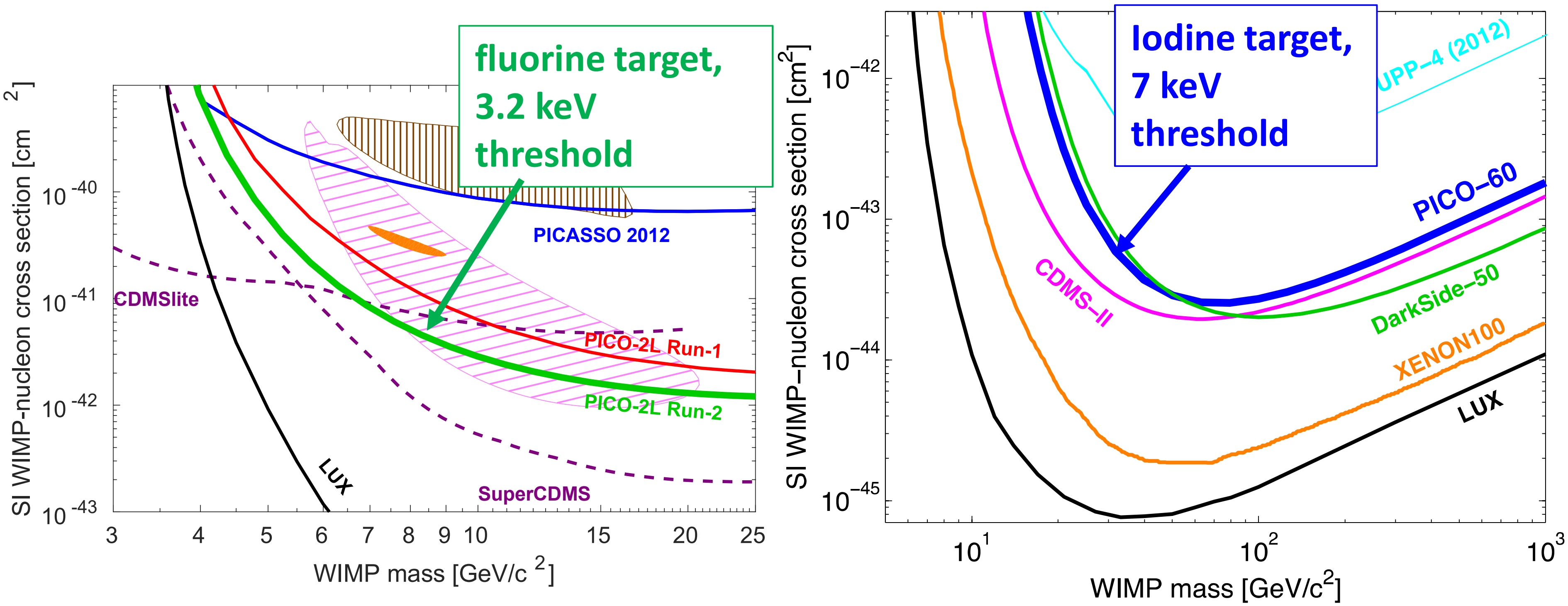



Phys. Rev. D 93, 061101 (2016)

# Limits on Spin-Dependent WIMP Cross Sections: PICO-60 & PICO-2L

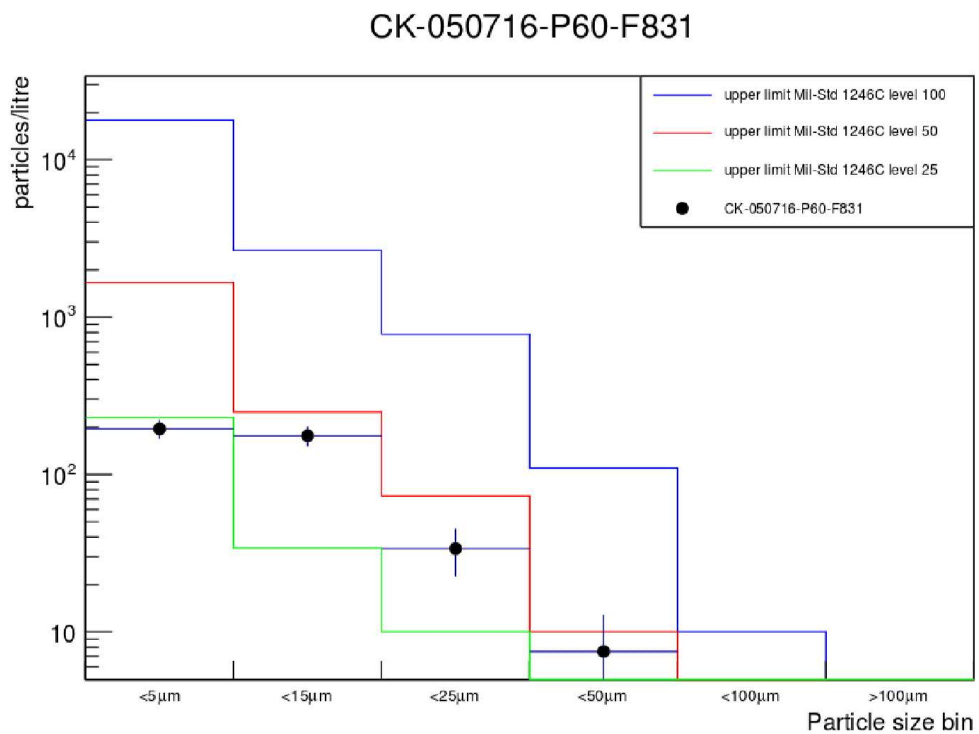


# Spin- Independent Limits



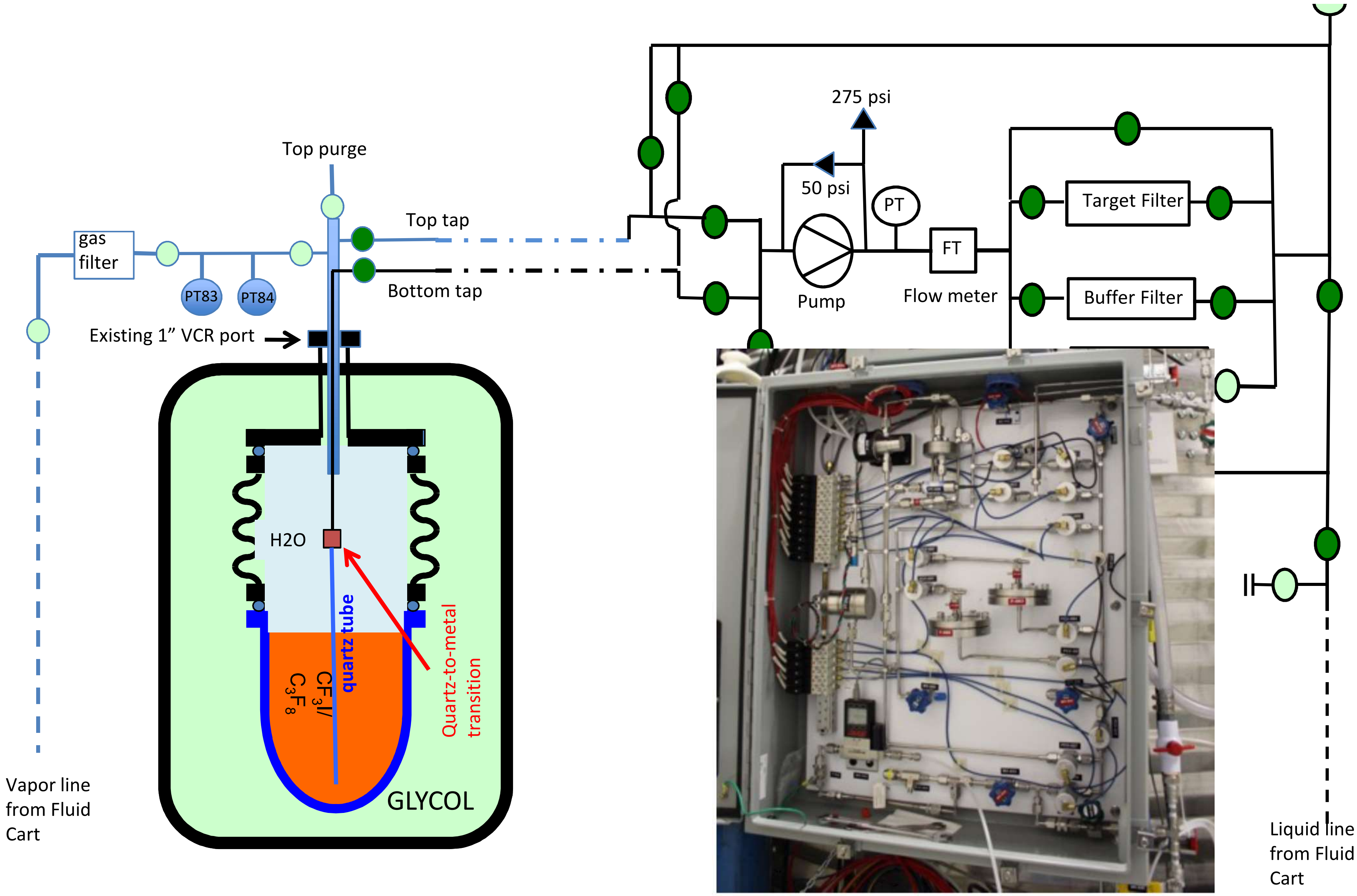
# Prep for new PICO-60 run- Inner Vessel Cleaning

- Spray jet cleaning with hot, filtered detergent.
- Particulate counting of waste water.
- Cleaned to quantitative standard- Mil spec 1246C level 50.



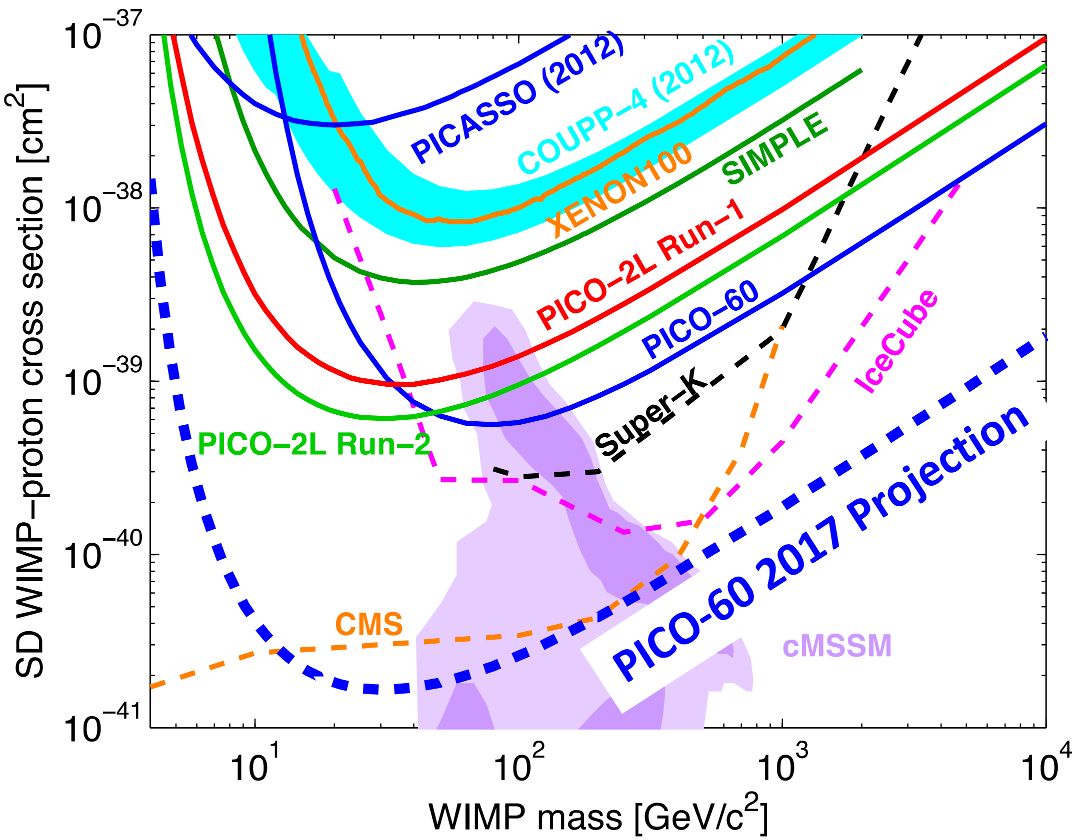
# PICO-60 Fluid Handling Upgrade for 2016-2017 Run

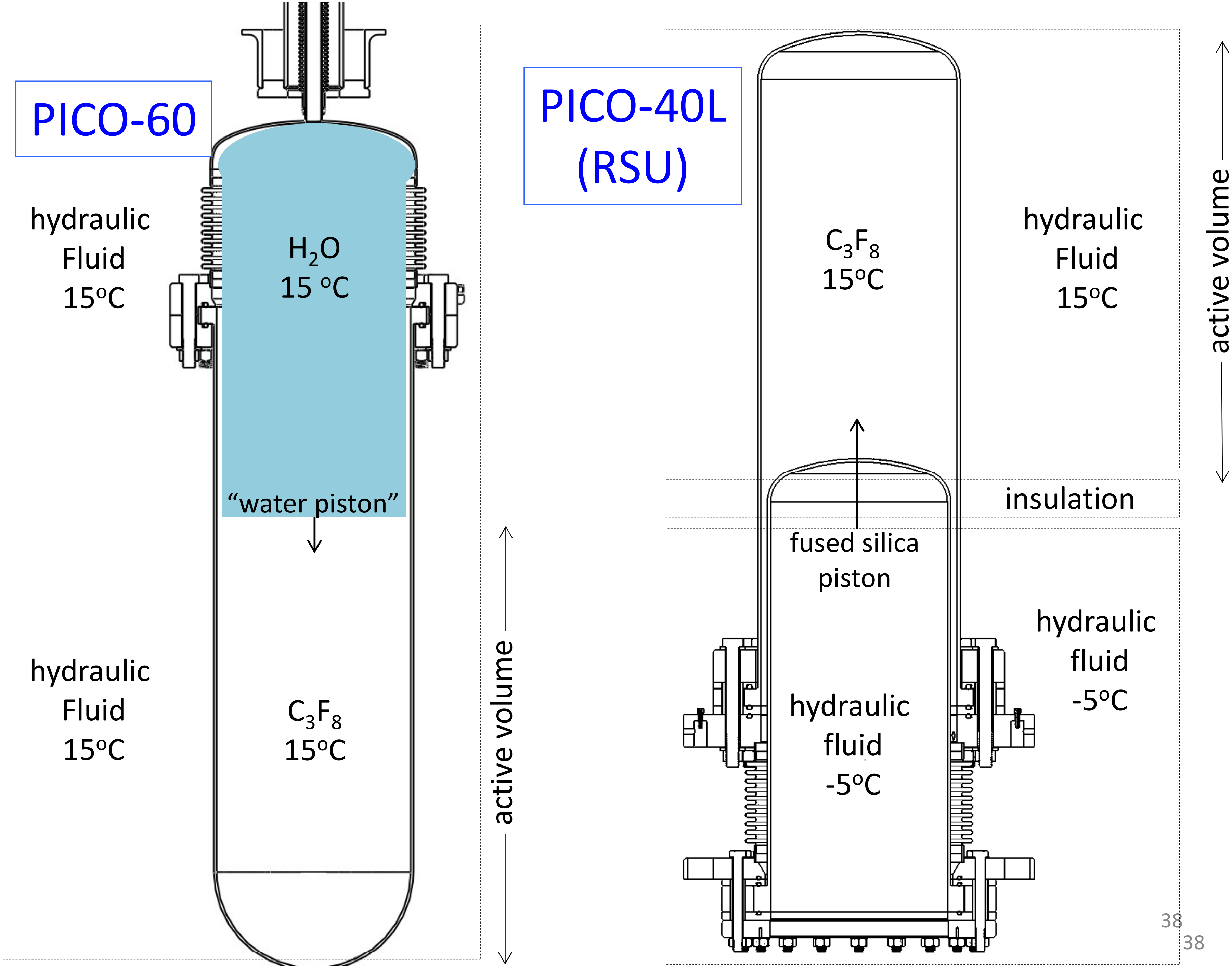
- Allows particulate counting and clean up during run



# New PICO-60 Run Underway Since August

- Cleaner Inner Vessel package, with new tools to monitor and maintain cleanliness.
- 60 kg C3F8 target.
- 3 keV threshold.
- > 75% live time fraction. >1000 kg-days exposure to date.
- Backgrounds appear to be very low.
- Blinded data since 11/28.




PICO-60
hydraulic Fluid 15°C
$H_2O$ 15 °C
"water piston"
hydraulic Fluid 15°C
$C_3F_8$ 15°C
active volume
PICO-40L (RSU)
$C_3F_8$ 15°C
hydraulic Fluid 15°C
active volume
insulation
fused silica piston
hydraulic fluid -5°C
hydraulic fluid -5°C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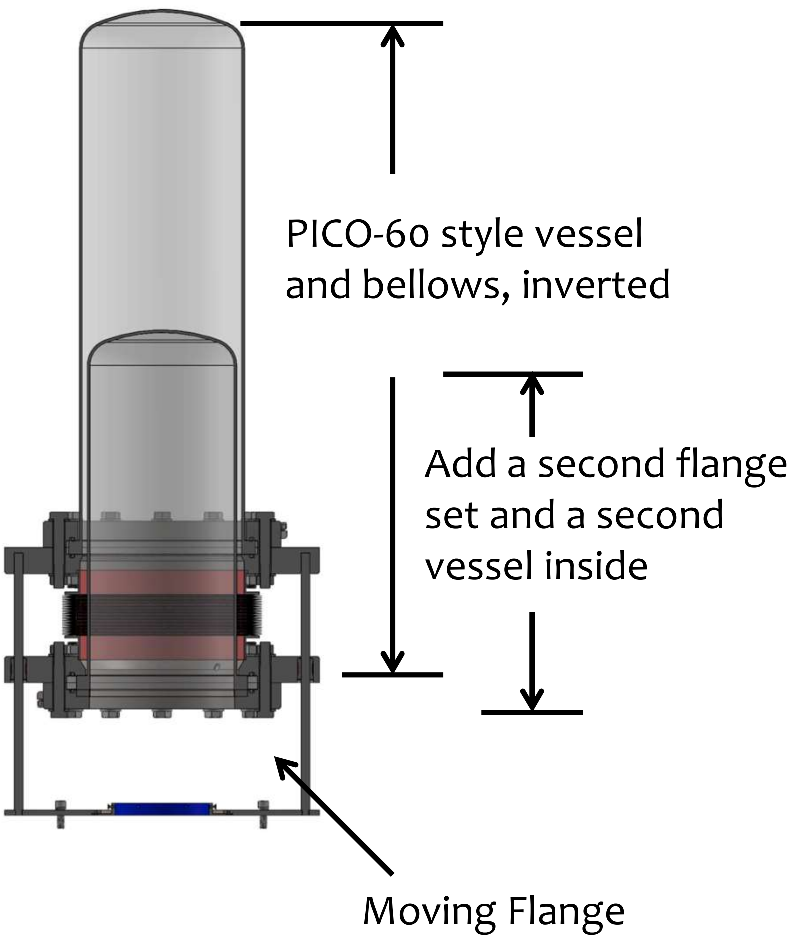
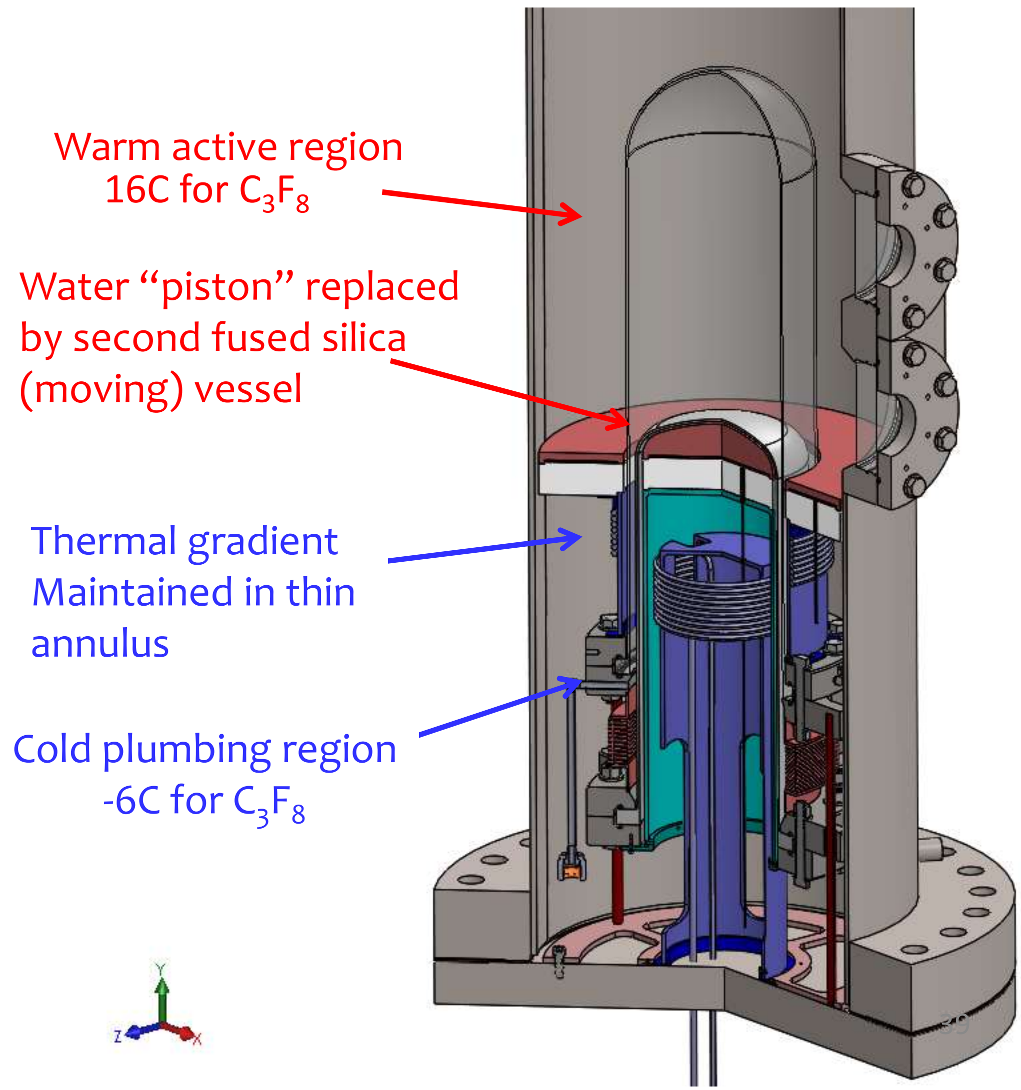
# PICO-40L: "Right-Side-Up"

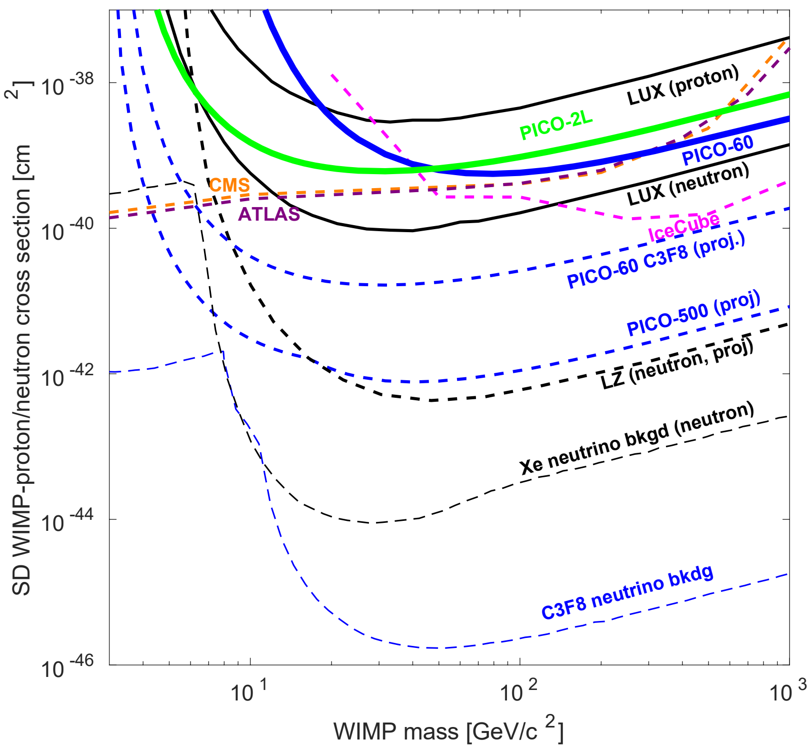
- Motivation- eliminate need for 2nd fluid (water) in inner vessel.
- Requires careful control of thermal gradient.

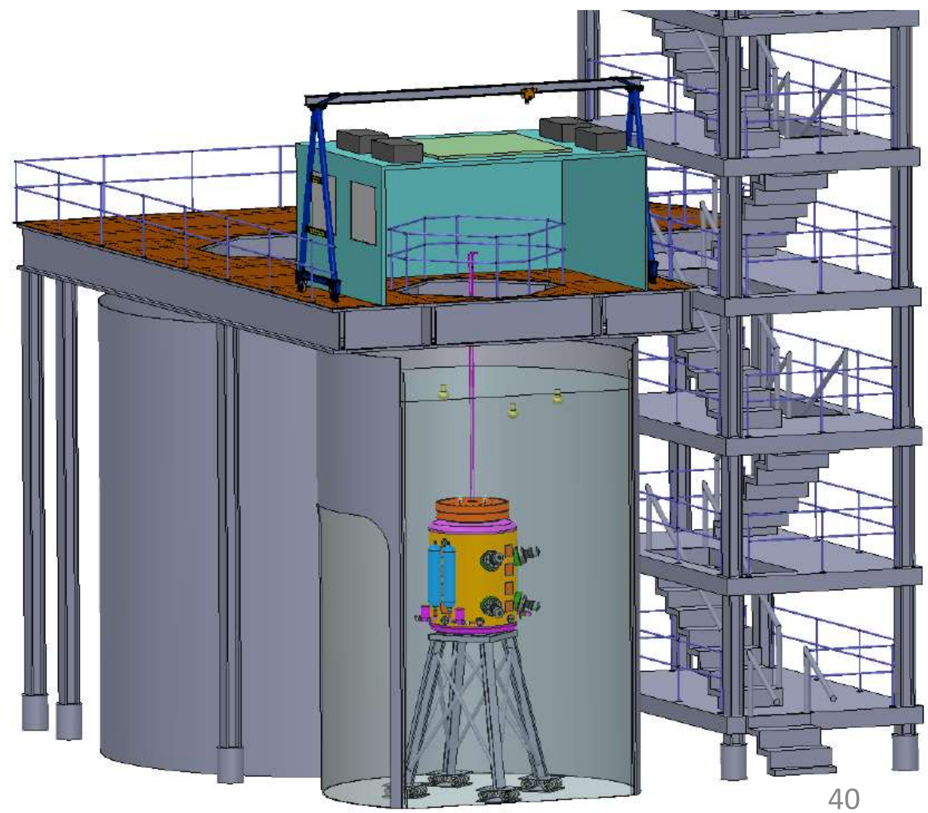


# PICO-500

- Ton – scale detector builds on design work funded by NSF and DOE for (unsuccessful) G2 project.
- PICO-500 proposal submitted to Canada Foundation for Innovation (CFI) this fall for infrastructure funding (~$4 million).



# Summary

- Leading sensitivity to spin-dependent WIMP interactions with protons. Our results keep getting better every year (or two)
- PICO-60 run is going well.
  - Backgrounds significantly reduced.
  - Should have improved results by Summer 2017.
- Main issue remains understanding precise nature of recoil-like background.
- Efforts to reduce particulate loading of the target fluid appear to be fruitful.